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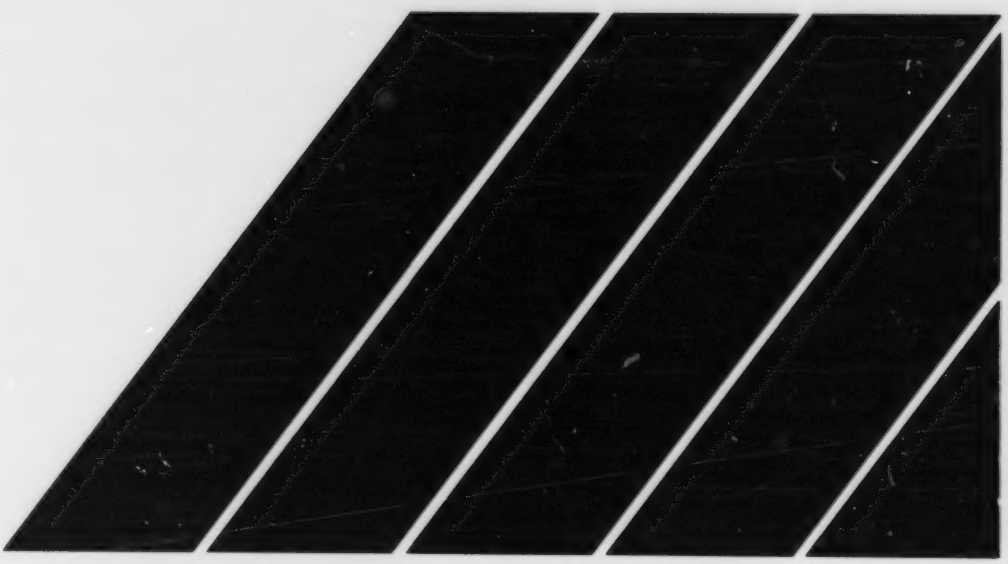
DEVELOPMENT AND EVALUATION OF HIGH-SPEED ELECTRONIC INJECTION SYSTEMS FOR THE DELIVERY OF NATURAL GAS TO THE INTAKE PORTS OF A HEAVY-DUTY ENGINE



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DEVELOPMENT AND EVALUATION OF HIGH-SPEED ELECTRONIC INJECTION SYSTEMS FOR THE DELIVERY OF NATURAL GAS TO THE INTAKE PORTS OF A HEAVY-DUTY ENGINE

PREPARED FOR:

Efficiency and Alternative Energy Technology Branch
Energy, Mines and Resources Canada
Ottawa, Ont.
DSS Contract No. 23216-8-9111/01-SQ
March, 1990

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77 pp

CITATION

B.C. Research Corporation and Ortech International. Development and Evaluation of High-Speed Electronic Injection Systems for the Delivery of Natural Gas to the Intake Ports of a Heavy-Duty Engine. DSS Contract No. 23216-8-9111/01-SQ. Efficiency and Alternative Energy Technology Branch, Energy, Mines and Resources Canada, Ottawa, Ontario. 1990 (39 pp.)

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NOTE

Funding for this project was provided by the Office of Energy Research and Development, Energy, Mines and Resources Canada.

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Catalogue No. M91-7/112-1990E
ISBN. 0-662-18127-1

EXECUTIVE SUMMARY

Current heavy duty natural gas engines rely on elementary fuel metering systems. In order to improve the efficiency and reduce emissions of these engines a more sophisticated fuel delivery system is required. One approach is the use of a gas valve for injection of natural gas into the intake ports. In this project an existing solenoid valve has been evaluated for this application. In addition, three prototype valves have been developed and tested.

The valves tested were:

(1) A production solenoid operated valve manufactured by Servojet Products Inc.

(2) A prototype solenoid operated valve developed by Ortech International, a subcontractor in this project

(3) A prototype continuous flow valve sized for one cylinder developed by B.C. Research

(4) A prototype continuous flow valve sized for an entire engine developed by B.C. Research, to be used with a fuel delivery manifold, or "spider"

The results are graphed and discussed. Each of the valves shows potential for successful commercial application. Recommendations are made for development of a port injection system on an engine installation.

RÉSUMÉ

A l'heure actuelle, les moteurs lourds propulsés au gaz propane sont équipés de systèmes rudimentaires pour mesurer le carburant. Dans le but d'améliorer l'efficacité de ces engins ainsi que de réduire les émissions qu'ils produisent, il serait essentiel de développer un système plus élaboré de distribution du carburant. On a déjà utilisé une auguille d'injection conçue pour l'essence pour la distribution du gaz naturel dans les orifices d'admission. Aux fins de ce projet, on a évalué une valve à solénoïde de ce type déjà existante. De plus, trois prototypes de valve furent développés et mis à l'essai.

Les valves mises à l'essai sont :

1) une valve solénoïdale de production fabriquée par Servojet Products Inc.;

2) un prototype de valve solénoïdale, développé par Ortech International, une entreprise sous-traitante, aux fins de ce projet;

3) un prototype de valve à arrivée continue de carburant pour moteur d'un cylindre, développé par B.C. Research;

4) un prototype de valve à arrivé continue de carburant conçu pour un moteur complet développé par B.C. Research.

Les résultats obtenues sont illustrés graphiquement et commentés. Chacune des valves semble s'avérer réussie sur le plan de la mise en marché. Des recommandations ont été faites pour le développement d'un système d'injection dans la lumière d'admission du moteur.

TABLE OF CONTENTS

	PAGE
1.0 INTRODUCTION	1
2.0 BACKGROUND	2
2.1 Engine Types	2
2.2 Fuel Injection Types	2
2.3 Functional Specification	3
3.0 REVIEW OF EXISTING TECHNOLOGY	5
3.1 Literature Search	5
3.2 Evaluation of Production Valves	6
3.3 Need for Prototype Development	7
4.0 PROTOTYPE DEVELOPMENT	7
4.1 Development of Continuous Port Fuel Injection System	7
4.2 Development of Timed Port Fuel Injection System	10
5.0 TESTING OF FUEL INJECTORS	23
5.1 Description of Test Equipment	23
5.2 Description of Injector Evaluation	23
5.3 Results	26
6.0 CONCLUSIONS AND DISCUSSION	35
REFERENCES	38
APPENDIX I - TABLES	
APPENDIX II - ENGINEERING DRAWINGS	

LIST OF FIGURES

FIGURE		PAGE
1	SPI HSV3000 Solenoid Operated Valve	8
2	B.C. Research Central Metering Valve	11
3	B.C. Research Central Metering Valve (Disassembled)	11
4	B.C. Research Port Injection Valve	12
5	B.C. Research Port Injection Valve (Disassembled)	12
6	E-Core Solenoid	14
7	Elongated E-Core Solenoid	16
8	Linear Multipole Solenoid	16
9	Ring-Shaped Multipole Solenoid	17
10	Injector Actuator - 3 Pole Linear Solenoid	17
11	Ortech Solenoid Operated Injector	19
12	Ortech Solenoid Operated Injector (Disassembled)	19
13	Capicative Discharge Solenoid Driver Circuit	21
14	Representative Solenoid Current and Pintle Lift Traces	22
15	Flow Bench	24
16	Gas Flow vs Value Position - B.C. Research Central Metering Valve	27
17	Gas Flow vs Value Position - B.C. Research Central Port Injection Valve	28
18	Gas Quantity vs Pulse Width - Ortech Solenoid Operated Valve	29
19	Gas Quantity vs Pulse Width - SPI HSV3000 Solenoid Operated Valve	30
20	Accelerometer Waveforem & Logic Pulse - Ortech Solenoid Operated Valve, Typical	31
21	Accelerometer Waveform & Logic Pulse - Ortech Solenoid Operated Valve, Average	32
22	Accelerometer Waveform & Logic Pulse - SPI Solenoid Operated Valve, Typical	33
23	Accelerometer Waveform & Logic Pulse - SPI Solenoid Operated Valve, Average	34

LIST OF TABLES

TABLE		
1	Functional Specification	4

1.0 INTRODUCTION

Progress has been dramatic over the last few years in the development of natural gas fuelled heavy duty engines for truck and bus use. However, with implementation of new, very strict California and Federal US heavy-duty emissions regulations scheduled for 1991 and 1994, the need for further refinement is indicated.

Natural gas carburetion systems in engine conversion kits presently on the market typically inject the gas at low pressure to a single point in or upstream of the intake manifold under mechanical or limited electronic control. With such systems, key factors in engine control including response time, accurate cylinder-to-cylinder fuel distribution, and control flexibility are necessarily less than optimal. Improvement in these areas may allow a natural gas fueled engine to meet upcoming emission regulations while maintaining power and minimizing engine stress.

A system providing these improvements would inject accurately metered quantities of natural gas to the intake port of each cylinder of the engine, as close as possible to the intake valve. Ideally, this would occur at high pressure to induce turbulence and stimulate mixing, and would take place in controlled pulses that coincide with the periods that the intake valve is open.

This type of system has been available for many years on automotive gasoline engines, and is used extensively in markets with stringent emissions and fuel economy legislation. However, the technology has not been applied to natural gas engines for two reasons: because, until recently, there has been no demand for improved natural gas systems; and because the great difference in volume between gaseous and liquid fuels makes gasoline injectors unsuitable for natural gas service. A natural gas injector needs to be much larger than a gasoline injector, and due to the higher weight of the moving parts, existing solenoid designs cannot work at speeds required for full load operation.

The objectives of the work described in this report are: to investigate the possibility of adapting existing technology to the requirements of port fuel injection for a natural gas heavy-duty engine; to develop a gas injection valve prototype by adapting existing technology if possible, or else, to determine two distinct design approaches and apply each to the development of a prototype injector; and to test the obtained equipment for suitability to heavy-duty engine requirements. Ultimately it is envisioned that the design will be tested in an engine in future work.

2.0 BACKGROUND

2.1 Engine Types

The first step in determining the functional requirements of a natural gas injector is to specify the engine or range of engines for which the valve is intended. The gas injector is intended for buses and trucks, so functional requirements were determined from the range of engines commonly found in these vehicles. These engines include two and four stroke types, horsepower ratings from 210 to 475, and rpm ratings from 2100 to 2800.

2.2 Fuel Injection Types

As the operating requirements of direct-cylinder injectors used on diesel engines have little in common with those of a natural gas injector, this review will concentrate on automotive gasoline injection systems, Furthermore, as single-point (manifold) injection systems have already been duplicated in natural gas engines, they also will be omitted from this discussion. The systems of interest are multi-point (port) fuel injection systems. Those commonly used for spark-ignition gasoline engines are of two main types, with a third type being a hybrid of the two.

2.2.1 Continuous Flow System

The simplest form of port fuel injection is the continuous flow system, with fuel supplied at high pressure to a central metering device, from which it is then distributed in equal quantities to each inlet port via a carefully designed fuel manifold or "spider". The advantage of this system is the small number of moving parts due to the flow being continuous and the need to control only one valve. A disadvantage is the difficulty of achieving a spider design having even fuel distribution. Since metering is done upstream of the spider, the designer must ensure that the variation in pressure drop among the individual fuel lines in the spider is within tolerable limits. One possible approach is to impose a relatively high pressure drop across the injector nozzle, so that the pressure drop in the fuel line is small by comparison, and any variation among fuel lines becomes insignificant. However, in the case of liquid fuel injection, injector nozzles sized for high pressure operation may be sensitive to wear and contamination.

2.2.2 Pulsed, Timed System

The most elaborate system is the pulsed, timed system, with a separate solenoid-operated valve at each cylinder. In this system, each solenoid opens during the intake stroke of each engine cycle, so that the fuel is always delivered while the intake valve is open. The solenoid valve has a constant flow rate when open, thus, fuel metering is accomplished by accurate control of the open period. The advantage of this system is, in principle, the best obtainable accuracy in fuel distribution due to timed metering of fuel taking place at

each cylinder. Injection of the fuel at the inlet port while the intake valve is open guarantees that the fuel goes into that cylinder and does not stagnate in the manifold and possibly get drawn into another cylinder by dynamic effects. However, it may be inferred from continued use of untimed systems in the automotive field that the theoretical advantages of timed injection are minor, i.e., difficult to isolate from other factors.

2.2.3 Pulsed, Untimed (Quasi-continuous) System

The hybrid type can be described as a pulsed, untimed or quasi-continuous system and consists of the same apparatus as the pulsed, timed system but with simpler control, in that the injection valves for all cylinders are actuated in unison once per engine revolution. Metering is still accomplished by varying the open period. The advantages of this system are accurate control of fuel distribution due to metering of fuel at each cylinder and lower cost for the control system as compared to the pulsed, timed system.

2.3 Functional Specification

From the requirements of the range of diesel engines of interest in this project, and the various strategies possible for spark-ignition port fuel injection systems, a functional specification for natural gas injectors can be determined. A table summarizing the performance specifications of these engines, the fuel requirement per cylinder, and the duration of intake event is in Appendix I. This information was used to draw up the functional specification for timed and continuous flow injectors (Table 1). Operational parameters in the functional specification are derived as follows:

Initial gas temperature T_1 - it is assumed that the natural gas will be warmed to near engine coolant temperature prior to metering

Manifold pressure P_2 - maximum manifold pressure (absolute) expected in the range of applicable engines

Sonic flow - For flow through a restriction with a constant upstream pressure and variable downstream pressure, mass flow calculation is simplified if the ratio of downstream pressure to upstream pressure is maintained at or below the critical ratio for sonic flow. With sonic flow and constant upstream pressure, the flow rate is independent of downstream pressure.

Upstream gas pressure P_1 - determined from manifold pressure P_2 and sonic flow condition

Turn down ratio - the ratio of maximum to minimum flow that the valve must meter accurately, i.e the ratio of full load to idle fuel requirement

TABLE 1
FUNCTIONAL SPECIFICATION FOR
HEAVY DUTY ENGINE PORT FUEL INJECTION

I. Fuel delivery Requirements

Assumed Conditions

Initial gas temperature T_1	353K
Manifold absolute pressure P_2	2.75 Bar
Sonic flow	$P_2 <= 0.544 P_1$
Upstream gas absolute pressure P_1	5.06 Bar
Turn down ratio	20:1

A. Untimed Fuel Injection (Pulsed or Continuous Flow)

Injector Mass Flow Q	3.09 g/sec
Valve Flow Coefficient C_v	0.0667
Metering accuracy maintained @ quantity	8.7 mg
Metering accuracy maintained @ flow	0.15 g/sec

B. Timed Fuel Injection

Injector Mass Flow Q	12.4 g/sec
Valve Flow Coefficient C_v	0.267
Metering accuracy maintained @ quantity	8.7 mg

II. Design Constraints

Max. size inside port	15mm ϕ x 50mm
Max. size outside port	75mm ϕ x 150mm
Design Life (solenoid injector)	1×10^9 cycles
Power Supply	8-14 Vdc
Operating Temperature	230 - 400K

Injector Mass Flow Q - for untimed (continuous flow) injection, the fuel flow requirement for one cylinder at full load; for timed injection, it is assumed that the maximum time available for injection is one-quarter of one cycle, so the fuel flow requirement for one cylinder at full load is multiplied by four.

Flow Coefficient C_v - standardized measure of flow restriction derived from flow conditions

Metering accuracy maintained @ quantity - for pulsed flow injectors, the fuel requirement per cycle at idle, i.e. 1/20 of full load requirement; quantity of gas injected must be repeatable from one cycle to the next at this condition

Metering accuracy maintained @ flow - for continuous flow injectors, the fuel flow requirement at idle, i.e. 1/20 of full load flow; flow rate must be identical each time this setting is selected

Maximum size inside port - allowable diameter and length of projection inside intake port

Maximum size outside port - allowable diameter and length of valve or nozzle body outside intake port

Design Life - projected number of opening and closing cycles for 500,000 miles of truck operation

Power Supply - voltage range of standard 12V automotive battery

Operating Temperature - range of temperatures encountered in automotive operations from winter cold starting to cylinder head operating temperature

3.0 REVIEW OF EXISTING TECHNOLOGY

3.1 Literature Search

A literature search for information on automotive fuel injection systems and industrial pneumatic valves including experimental designs was performed. The information collected represents the state of the art in solenoid valve and fuel injection technology at the time of the search.

3.2 Evaluation of Production Valves

Performance data obtained from the literature search was compared to the functional specification. No hardware was found with the right combination of characteristics for natural gas injection. Automotive solenoid injectors such as Bosch have ample actuation speed for timed injection of heavy-duty engines, but their flow coefficients are more than twenty times lower than that called for in the functional specification. Industrial pneumatic valves and solenoid operated valves with flow coefficients meeting or exceeding the required amount are readily available, however, their actuation speeds are ten times too slow for timed fuel injection.

3.2.1 Possibility of Modifying a Production Valve

One of the more interesting papers acquired in the literature search dealt with McCarley's development of a solenoid operated valve for gaseous hydrogen injection[1,2]. The requirements turned out to be very similar to those for the natural gas valve in this project. The paper discusses the process of examining available valves and comes to the same conclusions as did the present survey. Modifications to maximize the flow coefficient of a Bosch injector are also described in this paper; the flow coefficient (C_V=0.011) obtained is still nearly twenty times too low for present requirements. In light of this information the possibility of modifying a production valve was dismissed.

3.2.2 Possibility of Using Existing Experimental Valves

Several papers acquired in the literature search dealt with development of gas injection valves which showed some possibility of providing the speed and flow characteristics required in this project[1,2,3,4]. The most promising one was McCarley's solenoid operated hydrogen injection valve[1,2], which had ample flow capability and adequate speed. However, McCarley's work appears to have ended without demonstration or commercialization of his design. The hydrogen injector of Welch and Wallace[3] is reported to have worked adequately in their tests, although they do not provide any specific performance data. Their design was judged unsuitable for the present project due to the use of hydraulic actuation. Hydraulic actuation is undesirable, especially in spark-ignition engines, due to the added complexity of a hydraulic system and the risk of knock-inducing hydraulic fluid entering the combustion chamber.

A recent paper describes development of the Servojet Products Inc. (SPI) solenoid operated valve for injection of methane into a heavy-duty engine. This valve became available commercially after the decision to develop prototypes had been taken and prototype development was already well under way[4]. The manufacturer was contacted and performance of the valve was examined in comparison to the functional specification. The flow coefficient was below requirements, since the valve was originally designed for a higher operating pressure than the present specification. The

higher pressure allows a higher flow rate for a given orifice size; however, high delivery pressures at the engine do not allow full utilization of an on-board compressed fuel such as CNG; and the functional specification was derived with the lowest practical delivery pressure for this reason. Discussions with the manufacturer continued, however, and it was determined that a pair of these valves feeding one cylinder of a heavy-duty engine would satisfy the functional specification if operated in a quasi-continuous mode, i.e., remaining open for practically an entire cycle at full load, and being closed for part of the cycle as needed for less than full load operation. The manufacturer therefore agreed to supply a valve for testing on this basis. The SPI solenoid operated valve is shown in Figure 1.

3.3 Need for Prototype Development

Although one commercially available valve was eventually found, its application to the requirements of this project was somewhat marginal. To insure a good chance of achieving the project objectives, there was a clear need for the project team to develop two natural gas injector prototypes.

3.3.1 Design Approaches

According to the project objectives, two distinct technical approaches to the development of port fuel injection prototypes were required. Two design teams, Ortech and B.C. Research, were designated; and their areas of expertise were assessed in relation to the various approaches to port fuel injection design. Ortech had already gained some experience in solenoid injector design in earlier work in which an injector operating at 300 psi was developed and tested. B.C. Research's past work in dual-fuel engine technology included development of a continuous flow manifold injection system. Division of effort between the two design teams along these lines was suggested. A pulsed, timed injector operated by a high-performance solenoid would be developed by the Ortech project team, building on their past experience with this technology. The B.C. Research project team would develop a continuous flow port injection system based on their experience with continuous flow manifold injection of natural gas.

4.0 PROTOTYPE DEVELOPMENT

4.1 Development of Continuous Port Fuel Injection System

4.1.1 Background

In earlier work on dual fuel engines, B.C. Research developed a natural gas manifold injection system consisting of a commercially available plug type valve actuated by a automotive stepper motor. This system has proven flexible and reliable in a series of

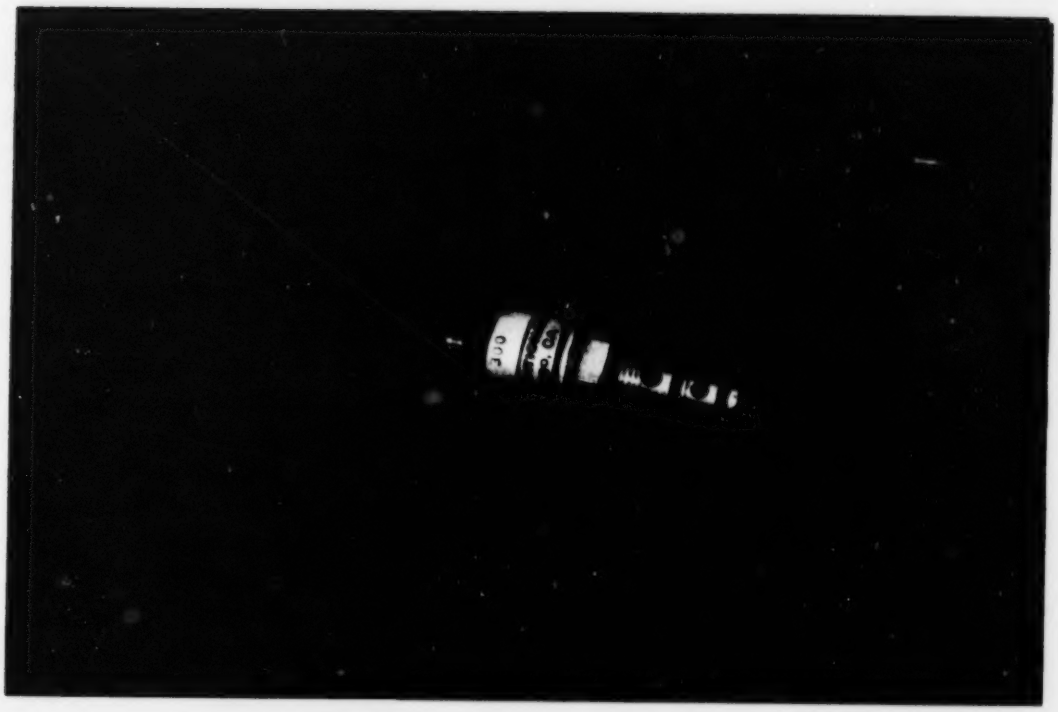


FIGURE 1
SPI HSV3000 SOLENOID OPERATED VALVE

dual fuel system development projects. For engines in the 400 hp range, the system features a 3/8" bore plug valve operating at 15 psi above manifold pressure, injecting natural gas into the intake charge at a point between the aftercooler and the intake manifold.

4.1.1 Central and At-Cylinder Metering

The project team was aware of the potential difficulties with fuel distribution in a continuous flow injection system using a fuel distribution spider. The initial approach chosen was therefore to design a continuous flow system with a metering valve at each cylinder. As this system was being planned, it was seen that, using the same driver, a continuous flow prototype with a central metering valve and fuel distribution spider could also be constructed. Thus, the decision to construct two continuous flow prototypes was taken, in order to study the relative merits of central metering and metering at each cylinder.

4.1.2 Theory of Operation

The metering valve operates in the same manner on both types of continuous flow systems. The valve must accurately control the gas flow rate, and change settings with adequate speed while maintaining accuracy. The differences between the two systems are:

(1) Compared with at-cylinder metering, the minimum and maximum flow rates for controlled metering in the central metering system are increased in proportion to the number of cylinders of the engine.

(2) The central metering system requires a carefully designed fuel distribution spider downstream of the valve to provide equal fuel delivery to all cylinders. While the at-cylinder metering system also requires a fuel manifold to provide fuel to each valve, it does not present great design difficulties since it is upstream of the point at which the metering takes place.

4.1.2 Description of Valve and Driver

Design of the continuous flow port injection systems was based on the existing B.C. Research manifold injection system design. Higher operating pressure of the port injection system permitted a small, 3/16" bore diameter plug valve to be specified for the central metering system feeding all cylinders. This valve was also considered for use in the at-cylinder metering system, however, examination of the valve opening versus flow curve showed that accurate metering for one cylinder would be difficult at low engine load, so a precision flow control needle valve of suitable capacity was specified instead.

For fast, precision actuation of these valves, a low-cost mass production automotive stepper motor of the type which has given excellent results in B.C. Research manifold injection systems was chosen. The two metering valves chosen had the same general construction and similar lift, so fitting the stepper motor to each was mechanically straightforward. One advantage of the smaller size of these valves as compared to the ealier low pressure manifold injection system is the that the lower mass and shorter travel of the stem allows faster actuation. Fitting the stepper motor to the valves is accomplished by removing the valve bonnet and stem, and fabricating a mechanical link between the stepper motor shaft and the valve stem. The valve bonnet is not used in the assembly. The stepper motor housing is bolted to the valve body and sealed at the interface with an O-ring. The resulting assembly is about the same weight as the standard valve, and slightly more compact. As part of the central metering injection system, a mock-up fuel delivery spider (not intended for an actual engine installation) was designed and fabricated, with adherence to the principle of equal length and equivalent bends in all branches. The central metering valve is shown in Figures 2 and 3, and the port injection valve is shown in Figures 4 and 5. Specifications and drawings for the two systems are included in the Appendix.

4.2 Development of Timed Port Fuel Injection System

Background

To effectively control the fueling of an internal combustion engine the automotive industry has found significant advantages of electronic controlled fuel systems. The advantages of electronic control are increased when the fueling is controlled on a per cycle basis with a pulsed injection of fuel for each power stroke of the engine. This method allows for fuel metering control by the pulse width being some fraction of a cycle. One unique characteristic of this type of system is its ability to react immediately to sudden change in fuel demand. It can also, under certain conditions, be used to create stratification of the air fuel charge within the cylinder.

These type of fuel injection systems are well established in the gasoline vehicle market and are quickly entering the diesel market. Most gaseous fueled engines however are still using mechanical continuous metering technology that was developed twenty or more years ago. Improvements made in liquid fueled engine efficiencie and emission due to new electronic controls has reduced the competitive edge gaseous fuels previously enjoyed.

There are some inherent hurdles to be overcome in developing injector technology for gaseous fuels. For example the volume of natural gas which must be injected per cycle is roughly 7-10 times that of the diesel fuel per cycle for equivalent energy. This requires

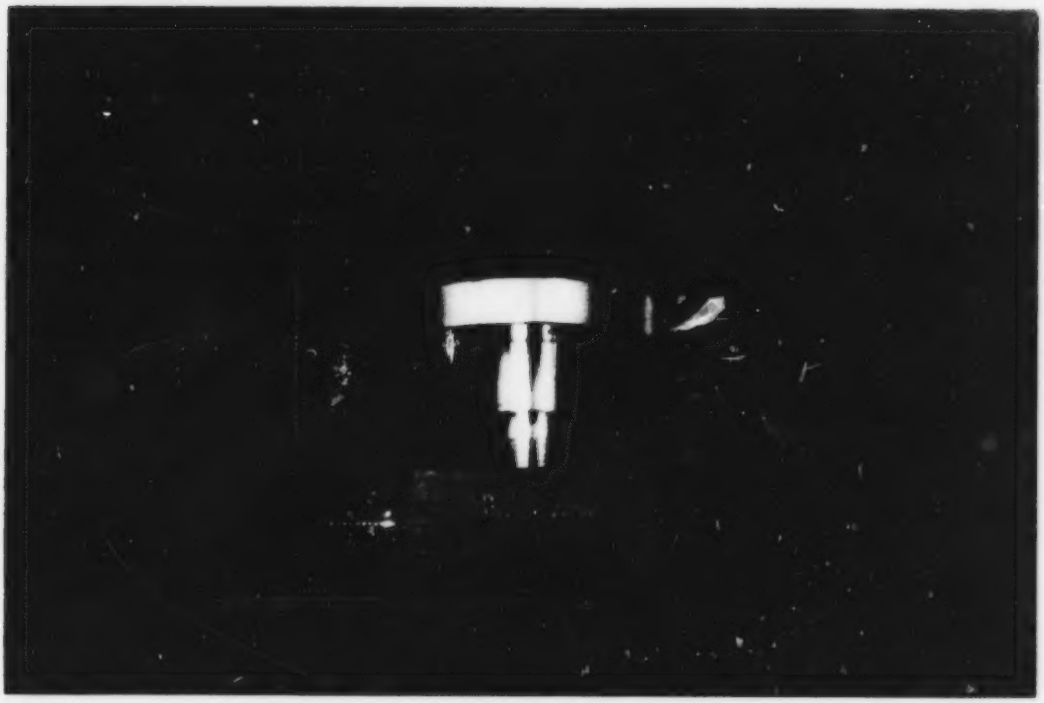


FIGURE 2
B.C. RESEARCH CENTRAL METERING VALVE

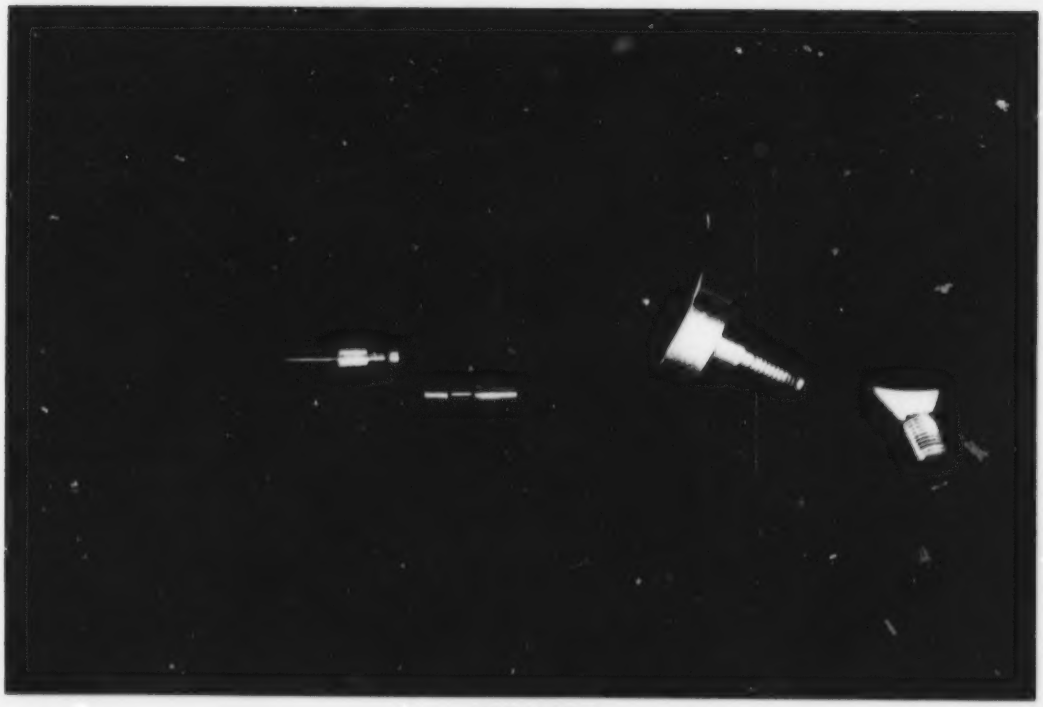


FIGURE 3
B.C. RESEARCH CENTRAL METERING VALVE (DISASSEMBLED)

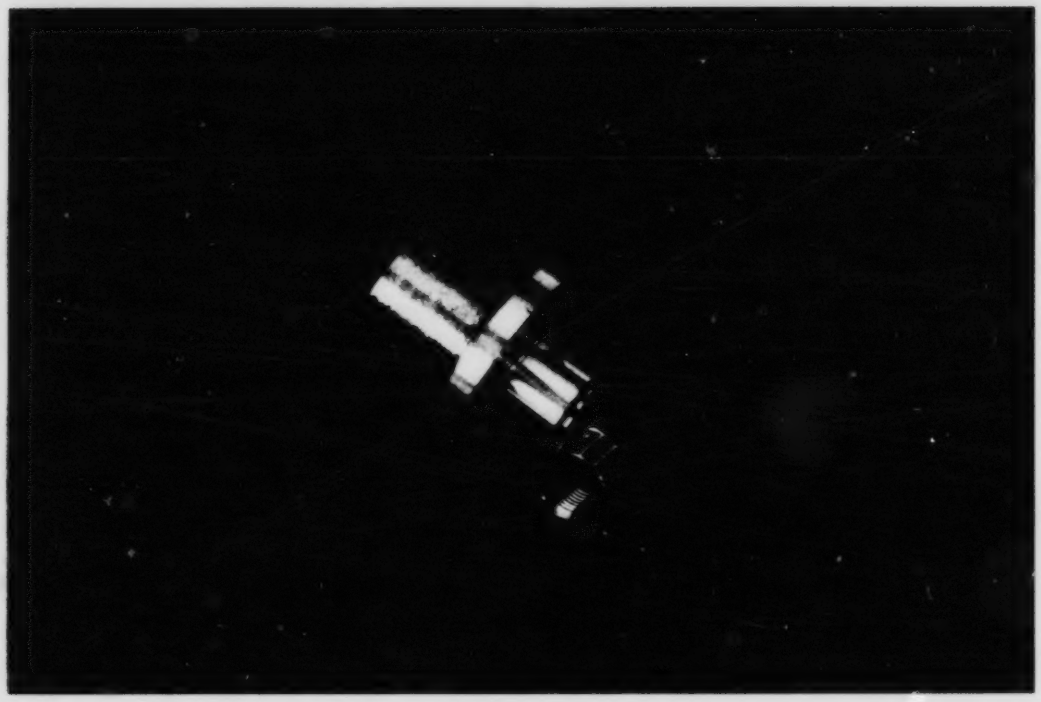


FIGURE 4
B.C. RESEARCH PORT INJECTION VALVE

FIGURE 5
B.C. RESEARCH PORT INJECTION VALVE (DISASSEMBLED)

injectors with larger flow passages and higher pintle lifts. Current injectors used in the industry for liquid fuels could only supply approximately 5 to 10 percent of the natural gas required for a heavy duty diesel engine.

Theory of Operation

Fuel injection equipment for diesel fuels fulfills two functions, pressurization and metering, although the pressurization function is not usually explicitly recognized. Since gaseous fuels are highly compressible the normal plunger type pump which pressurizes and meters the liquid fuels simultaneously cannot be used. Pressurization and metering of gaseous fuels must be accomplished separately. The function of a gaseous fuel injector is to deliver a metered amount of already pressurized gas. Thus, it is really a timed admission valve rather than an injection, although the latter terminology will be used for brevity.

In the design concept employed here, fuel metering is accomplished by controlling the duration of injector opening while maintaining a fixed gas supply pressure. The injector is essentially an on-off switch - it opens completely as rapidly as possible and closes as rapidly as possible, with the fully open flow rate controlled by the nozzle orifice size and the differential pressure across the orifice. Use of a gas supply pressure sufficient to achieve choked flow in the nozzle orifice eliminates the dependence of the flow rate on pressure downstream of the orifice. Assuming that the actuating and closing times do not vary with frequency of operation, pulse width control of the trigger pulse applied to the solenoid driver circuit provides control of the quantity of fuel delivered. This is a simple and direct method although it demands fast injector response.

The design of the injector was based on direct electromagnetic actuation using a high energy multipole solenoid. Although the actuating power requirements are higher than those of electrohydraulic actuation, the simple design and freedom from dynamic seals made it the option of choice

Design of a solenoid actuator involves a compromise between the force developed and the speed of operation. The interrelationship between these two parameters is best illustrated by considering a conventional E-core solenoid as shown in Figure 6. (The following discussion if based on material presented by Seilly[15]. The maximum practical force for a given face area is limited by the magnetic saturation of the material. Thus, for a given material the maximum force is proportional to face area. The acceleration of the armature depends on its mass and the force applied to it. Figure 6 shows that the armature mass of the conventional E-core solenoid is proportional to $6x^3$ while the face area is proportional to $4x^2$. Thus, as the dimension "x" is increased to achieve larger force, the armature mass increases much more rapidly (x^3 vs. x^2) which results in lower acceleration, hence slower response.

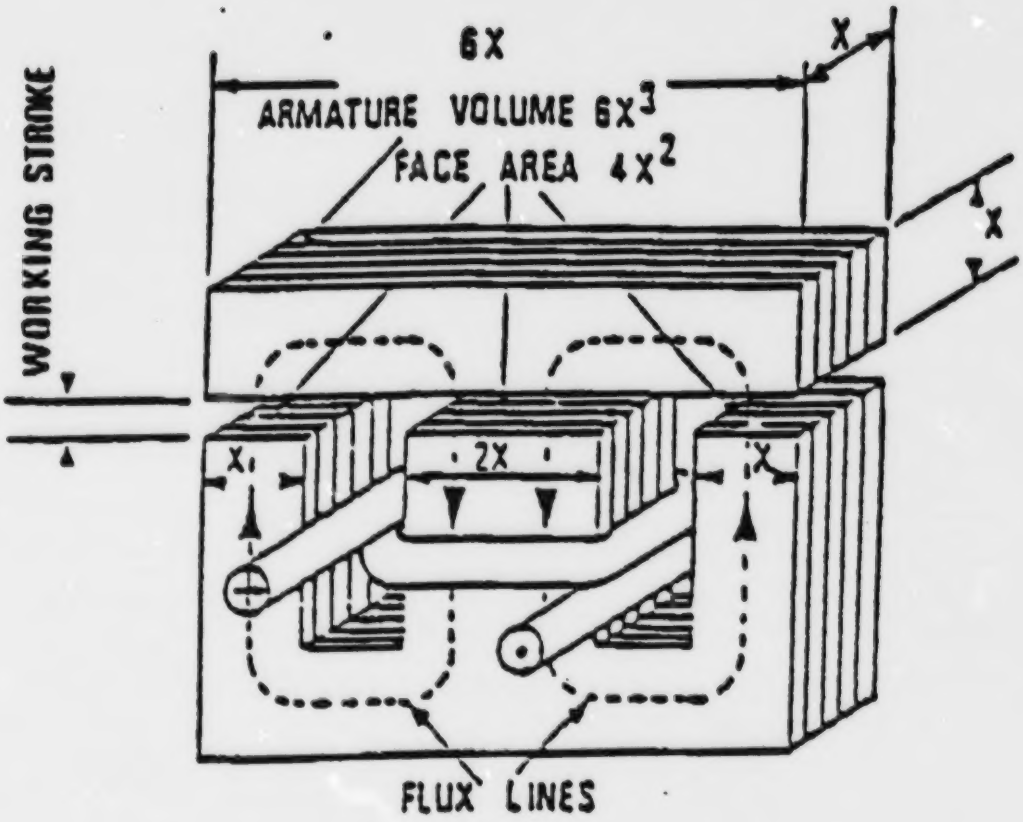


FIGURE 6
E-CORE SOLENOID

Seilly[15] noted that elongating the solenoid as shown in Figure 7 provides a means of decoupling the force and acceleration. Both the mass of the armature and the total force developed are increased in direct proportion to an increase in length. The dimension "x" may be varied to achieve the desired acceleration. The utility of the elongated E-coil solenoid is limited by the lack of rigidity of the armature as the length in increased[15]. Seilly was able to overcome this limitation by rotating the traction faces 90 degrees and by bending the elongated solenoid into a helix (in the case of the Helenoid[15] or into concentric rings of increasing diameter (in the case of the Colenoid[16]).

The linear multipole solenoid shown conceptually in Figure 8 has the same characteristics as the elongated E-core solenoid, i.e. the ratio of the armature mass to the face area remains constant as it is extended. Here again the rigidity of the armature is the limited factor. Bending the linear multipole solenoid into a ring with sector shaped poles, as shown in Figure 9 is one way to achieve sufficient rigidity. Shechter[17] discusses the performance of this type of solenoid. In the present project the arrangement shown in Figure 10 was used. The design is a linear multipole solenoid with 3 coils having ribs of different lengths chosen to fit the maximum face area into the available diameter. Annealed mild steel was used for both the coil core and the armature. Although other materials can support a higher flux density, they often have a higher residual magnetism after the coil current has been removed[18]. This could result in slow or erratic amature return response.

In order to achieve the desired net actuating force, the estimated efficiency of a high speed solenoid, about 30%[19], must be taken into account to determine the theoretical traction force to be used as the design target. The maximum theoretical force developed by a solenoid is give by[20].

$$F = \frac{B^2 A}{2\mu_0} \qquad (1)$$

where:
- F = force in Newtons
- B = flux density in Tesla (Weber/m^2)
- A = traction face area in m^2
- μ_0= permeability of free space ($4\pi \times 10^{-7}$)

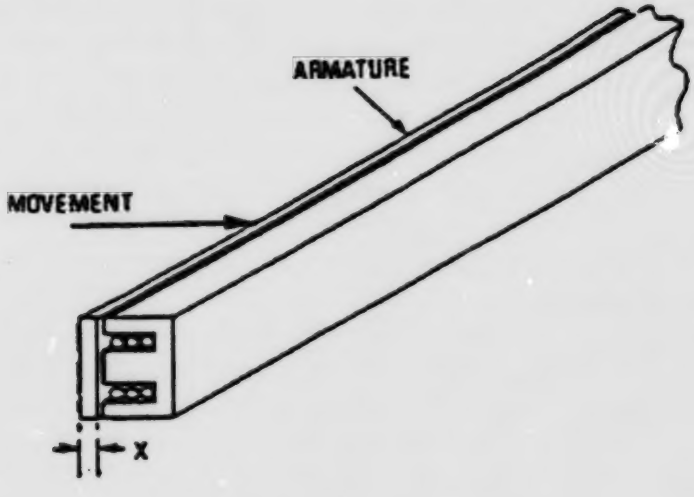


FIGURE 7
ELONGATED E-CORE SOLENOID

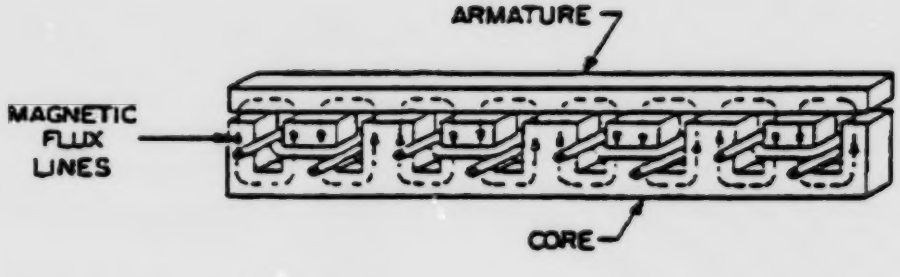


FIGURE 8
LINEAR MULTIPOLE SOLENOID

FIGURE 9
RING-SHAPED MULTIPOLE SOLENOID

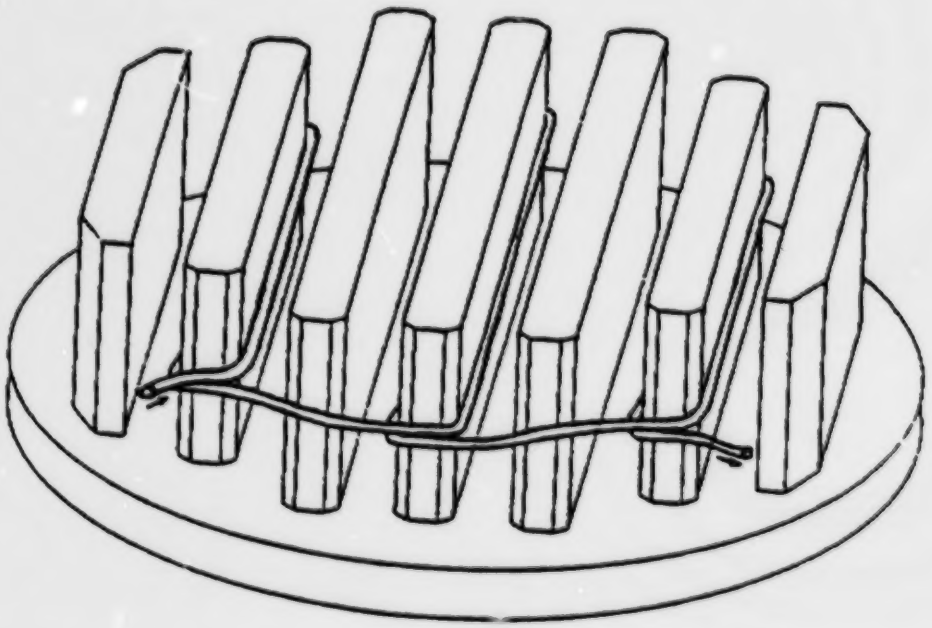


FIGURE 10
INJECTOR ACTUATOR - 3 POLE LINEAR SOLENOID

Assuming that magnetic saturation occurs in mild steel at approximately 1.7 Teslas, the solenoid face area required to achieve the theoretical actuating force may be calculated using equation (1). An approximate value of the ampere-turns required to achieve magnetic saturation may be estimated from the following equation[20]:

$$Ni = \frac{Bl}{\mu_0} \qquad (2)$$

where: N = number of turns per pole
i = current in amps
l = length of the air gap in meters

The choice of specific N and i values is a compromise. Ideally a low value of N (hence a low value of inductance) with a high current provides the required force with a small time constant. However, high currents require large diameter wire as well as expensive components in the driving circuit. Wire of 24 AWG was chosen for ease of coil winding, while still having reasonable current carrying capacity. This information along with the face area required determined the coil dimensions.

Description of Valve

The prototype injector, shown in Figures 11 and 12, consists of four main parts: the injector tip, injector head, injector cap and the armature/pintle assembly. The large diameter head was required to develop sufficient actuator force.

The stainless steel injector tip threads onto the injector head. By having an adjustable tip locking ring on the injector head, the tip can be screwed on and locked at various depths, which allows for adjustment of the stroke by moving the armature disk closer or further away from the coil ribs. The proper spring preload is achieved by control of the thickness of the spring spacer. The seat is made of 3140 carbon steel and heat treated to a hardness of 55 Rockwell 'C'. This seat is pressed into the injector tip. The seat face is at an angle of 60 degrees to the axis through the flow passage.

The injector head was made of brass because it is non-magnetic and easy to machine. The pintle armature assembly with a mass of 44 grams, is the only moving part. A high rate coil spring, (900 lbf/in), was used to supply preload and closing force to the pintle. The injector cap, made of annealed mild steel, served as the solenoid core.

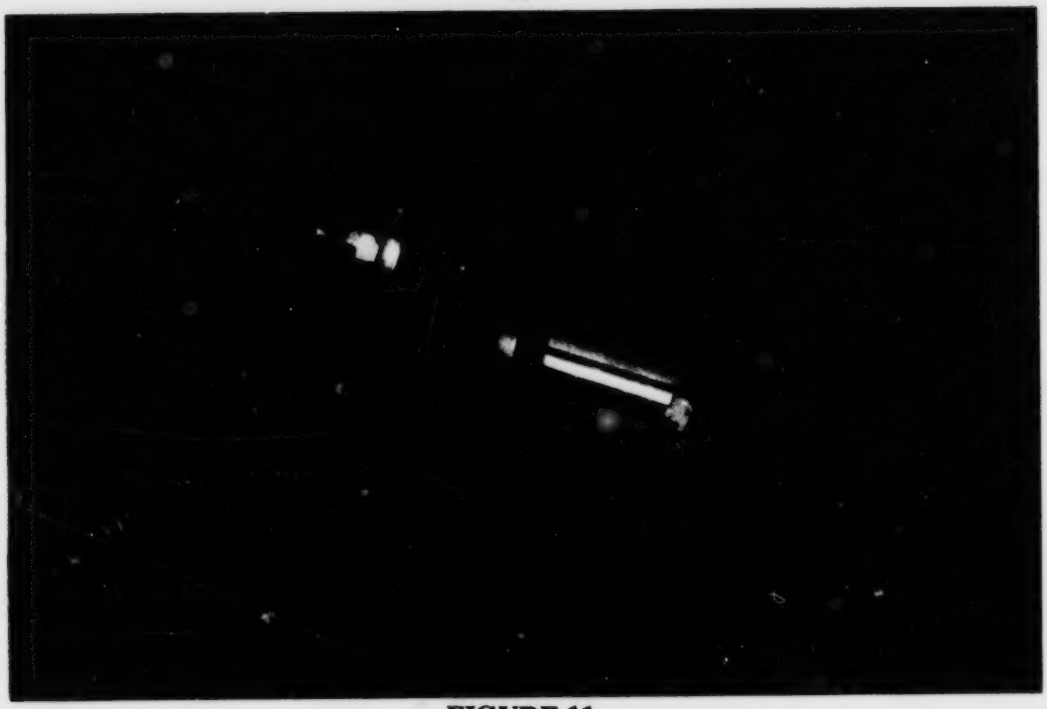


FIGURE 11
ORTECH SOLENOID OPERATED INJECTOR

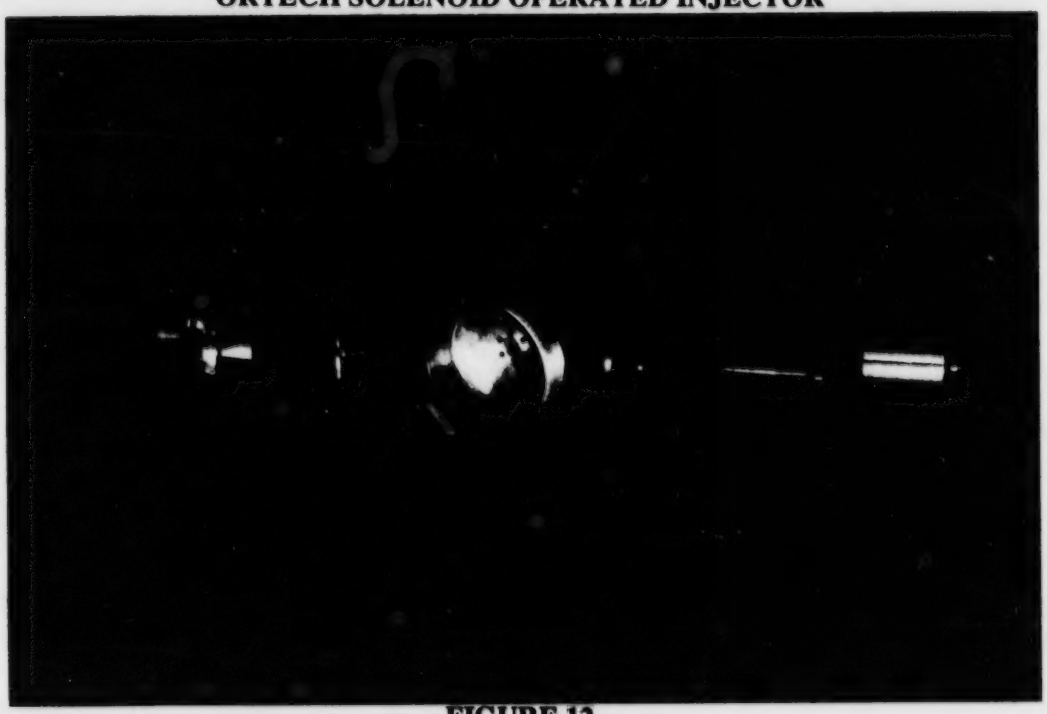


FIGURE 12
ORTECH SOLENOID OPERATED INJECTOR (DISASSEMBLED)

Solenoid Driver Circuit

To achieve fast response, a capacitive discharge driver was used. The need for a high initial voltage may be seen by examining the equation governing the voltage across an inductor (coil):

$$V = L \frac{di}{dt} + i(t) R \qquad (3)$$

where: L = coil inductance
R = coil resistance

Solving equation (2) for B and substituting into equation (1) shows that the force developed by a solenoid depends on i^2. Thus, "i" must be increased as quickly as possible. Initially, i.e. when i (0) = 0, equation (3) shows that for a given inductance the rate of increase of the current is directly proportional to the voltage applied. Thus, the initial rate of increase of force, and therefore response time, is improved by increasing the voltage.

Figure 13 shows the circuit of the capacitive driver used, which was based on a circuit developed earlier by MacCarley[1]. Note that two supply voltages are needed: 100 VDC to charge the capacitor and 12 VDC to provide holding current. For testing of the prototype injectors, the 100 VDC was supplied from a laboratory power supply. Vehicle application would of course have to use a DC to DC converter to provide the 100 VDC, as has been done for capacitive discharge ignition systems in the past. Operation of the driver is as follows: the capacitor is charged to 100V through a current controlling resistor (R1). When the FET switch (IRF 250) closes in response to the rising edge of a trigger pulse, the capacitor is discharged through the coil to ground. This initial high voltage causes the armature to be pulled against the coil core. With the air gap between armature and coil reduced, only a small current is needed to hold it there. The holding current is supplied by the 12 VDC input through an adjustable resistor (R3). The operating cycle is terminated when the FET switch opens in response to the falling edge of a trigger pulse. Thus, the opening duration is controlled by the trigger pulse width.

Note that when the FET is opened ($i \rightarrow 0$), a large reverse voltage spike is produced by the inductance of the coil (see equation (3)). Typically, switching transistors are protected from this voltage spike by installation of a protection diode across the coil terminals such that it is reverse biased during normal operation. However, the discharge path provided by this diode leads to long current decay times and thus long valve closure times. MacCarley[1] overcame this problem by connecting the protection diode (d1) so as to be forward biased from the drain of the FET to the high voltage supply. This arrangement prevents current flow for reverse coil voltages up to the level of the high voltage supply,

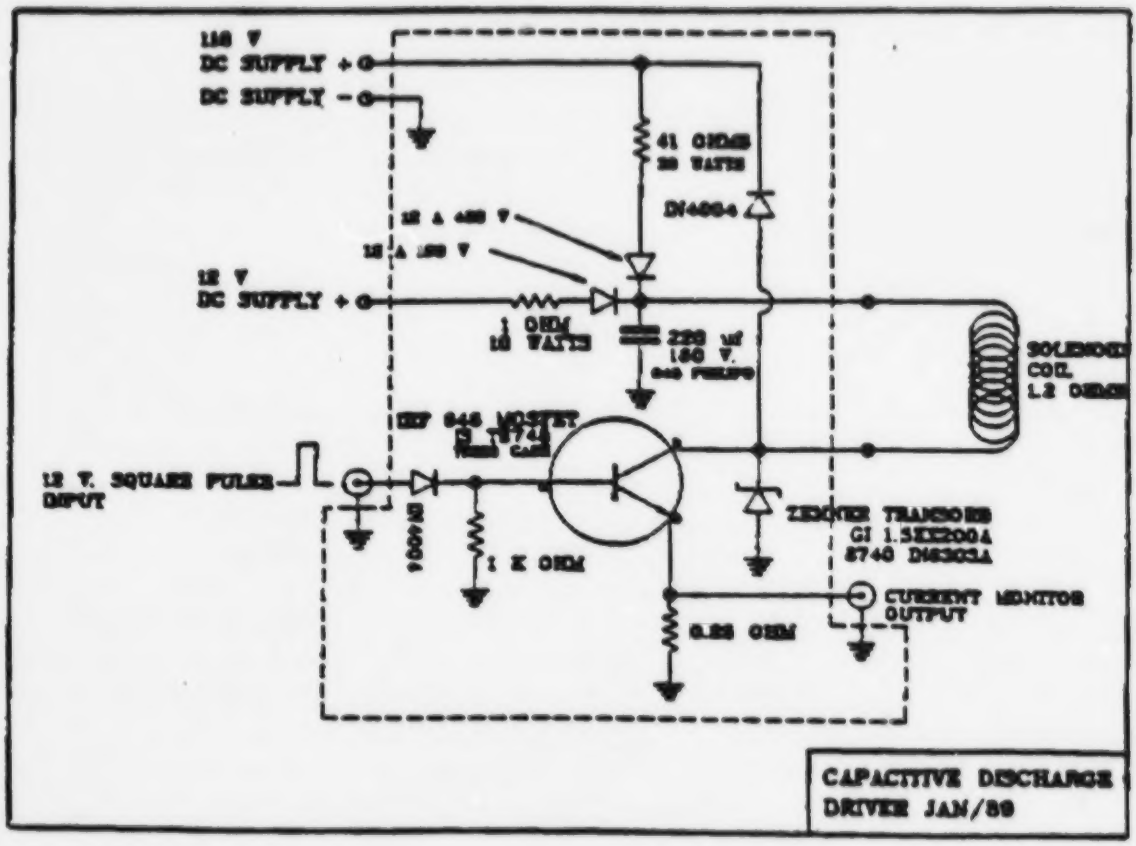


FIGURE 13
CAPICATIVE DISCHARGE SOLENOID DRIVER CIRCUIT

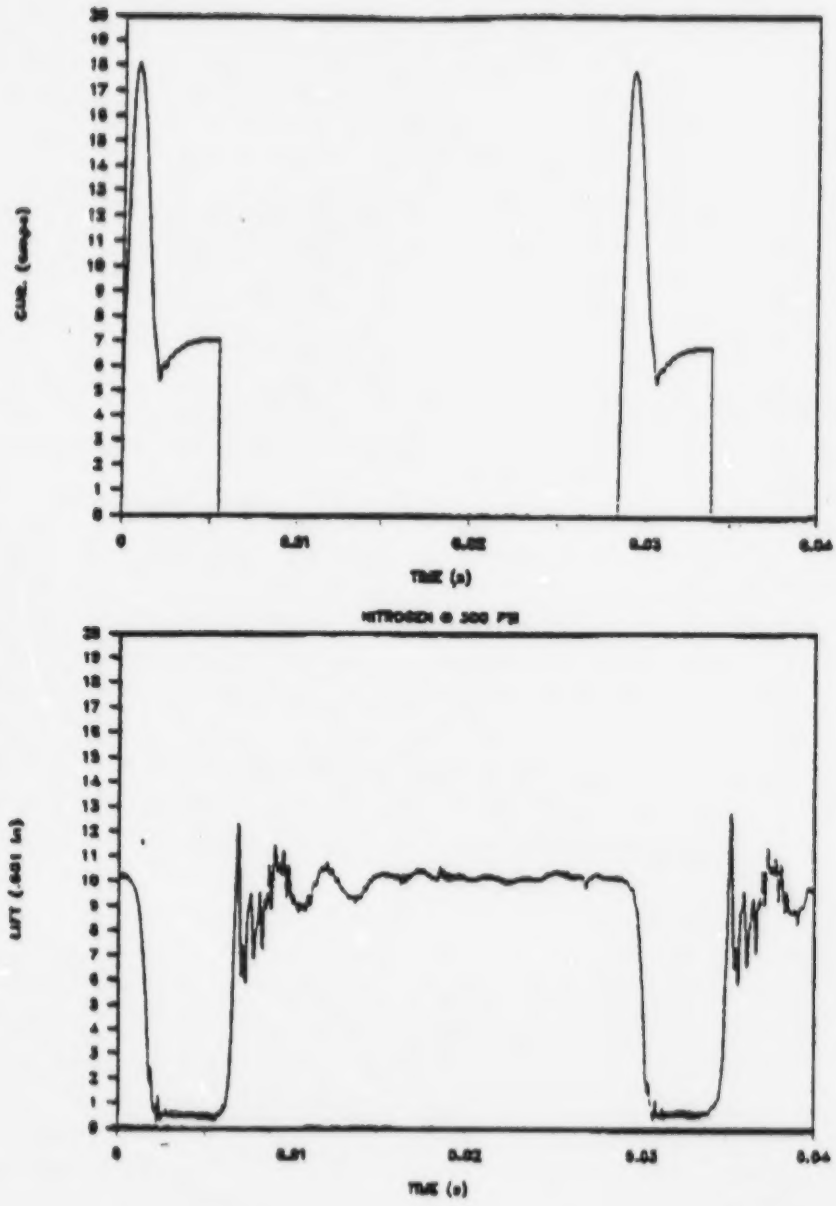


FIGURE 14
REPRESENTATIVE SOLENOID CURRENT AND PINTLE LIFT TRACES

at which point protection is provided by current flow through (R1). Backup FET protection is provided by zener diode (D2). A 1/4 ohm resistor (R2) was included in the driver circuit for monitoring coil current. Figure 14 shows representative driver current and pintle lift traces. Note the rapid current rise to a peak value and the sharp drop off to the lower holding current value. The latter indicates correct sizing of the capacitor. Note also the very fast current decay for closing.

5.0 TESTING OF FUEL INJECTORS

5.1 Description of Test Equipment

An integral part of this project was the design and construction of a natural gas flow bench. Important features of the test bench are:

(1) Flow capacity in excess of full load demand of a 425 hp natural gas engine

(2) Instrumentation for pressure, temperature, and flow rate as needed upstream and downstream of the test piece

(3) Computerized control of valve testing parameters and computerized data acquisition

(4) Two heated regulators and heat exchanger to maintain stable gas conditions

The flow bench is shown in Figure 15.

5.2 Description of Injector Evaluation

The tests are intended to evaluate the suitability of the injection systems under controlled conditions representative of actual engine operation. Their performance is measured and compared to the functional specification. The areas of evaluation are:

(1) Fuel delivery versus pulse duration (pulsed valves) or valve position (continuous flow valves). Test conditions simulate idle to full load operation at speeds from 600 to 2100 rpm

(2) Statistical error in open duration or valve position (valve position inferred from flow rate for continuous flow valves; open duration inferred from accelerometer trace of opening and closing for solenoid valves)

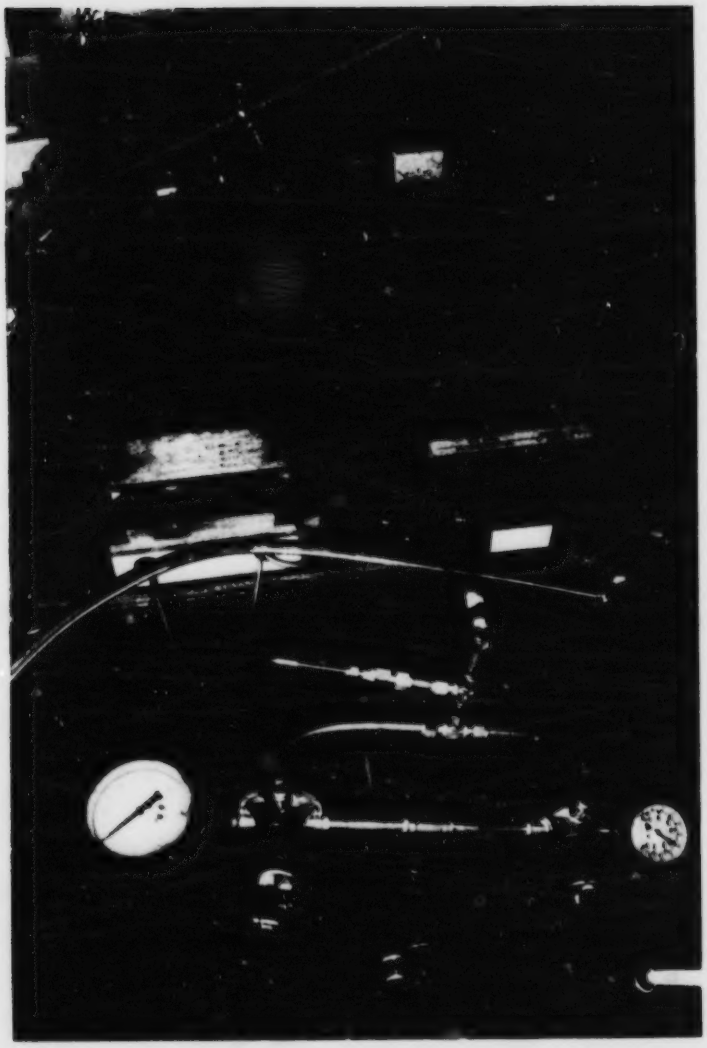


FIGURE 15
FLOW BENCH

(3) Flow variation among branches of the mock-up spider for the centrally metered continuous flow injection system

(4) Durability testing of valve mechanism followed by analysis for leakage, wear, and functional impairment

(5) Incidental experience gathered in testing and analysis of significant or unusual design features

5.2.1 Test Methodology

(i) Flow testing of Ortech and SPI solenoid operated valves: For each test, the valve driver was set to a frequency and pulse width representing a particular engine rpm and load. Data on gas quantity, pressure and temperature were taken for approximately two minutes.

(ii) Flow testing of B.C. Research continuous flow valves: For each test, the position of the valve was set via the stepper motor controller to represent a particular engine load. Data on gas quantity, pressure and temperature were taken for approximately 30 seconds.

(iii) Repeatability testing of Ortech and SPI solenoid operated valves: Nineteen accelerometer traces were generated showing a single valve opening and closing event against the logic pulse. A baseline was generated showing the average of 500 superimposed accelerometer traces, each triggered from the beginning of the logic pulse.

(iv) Repeatability testing of B.C. Research continuous flow valves: The valve was cycled approximately 20 times from full open to a low flow position using the highest intended actuation speed. The low flow setting was maintained for 20-30 seconds while flow, temperature and pressure data were collected.

(v) Measurement of flow variations in branches of fuel delivery spider: The spider was installed on the flow bench with no metering valve upstream, to ensure that the spider was the governing flow restriction. Data on flow, pressure and temperature were taken for approximately 20 seconds for one branch at a time while the others were blocked off.

(vi) Durability testing of Ortech and SPI solenoid operated valves: The time to leakdown from 80 to 40 psi was measured prior to durability testing. The valves were connected to building compressed air and cycled at a frequency corresponding to 2100 engine rpm. The time to leakdown from 80 to 40 psi was again measured at the end of testing.

5.3 Results

Flow data for the graphs were averaged over a period where conditions had stabilized and were then corrected to standardized temperature and pressure (5.0 bar & 353K). The calculation is as follows:

$$Q_{corr} = Q_{meas} * (5.0/P_{av}) * (T_{av}/353)^{1/2}$$

Where:

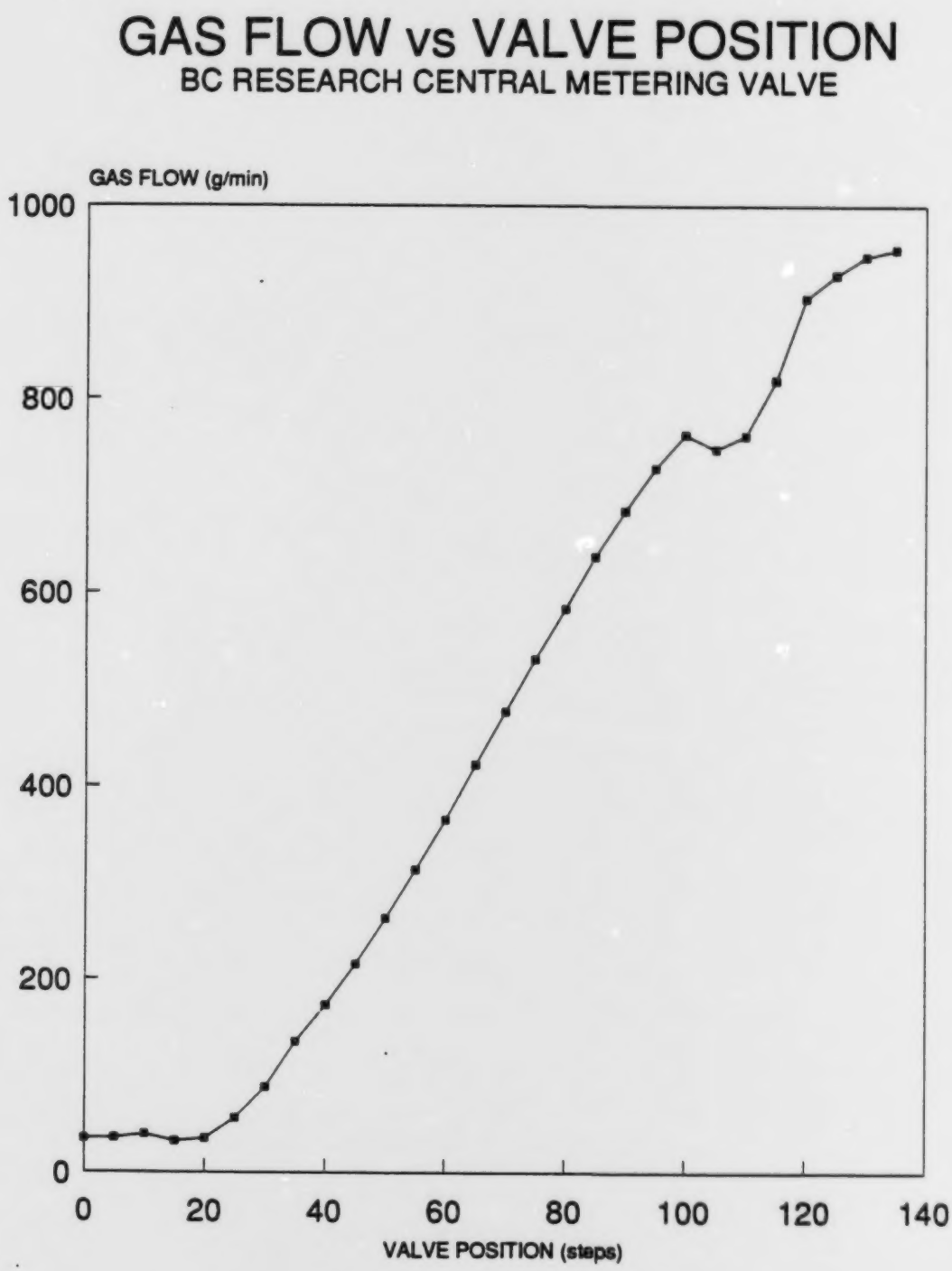
Q_{corr} = Corrected flow
Q_{meas} = Uncorrected flow
P_{av} = Average pressure (Bar, absolute)
T_{av} = Average temperature (K)

5.3.1 B.C. Research Central Metering Valve and Spider

Flow vs valve position is shown in Figure 16. The flow is linear with valve position over a large range. The linear range encompasses the assumed idle fuel requirement of 54 g/min, but the target maximum flow of 1080 g/min is not reached. At approximately 100 steps, or 780 g/min, there is a local peak in flow. At approximately 110 steps, again at 780 g/min, the flow rises sharply, then levels off at 960 g/min. A table of repeatability results appears in Appendix I. The standard deviation in 22 iterations of selecting idle fuel flow setting of 24 steps (approximately 54 g/min) from a starting position of 122 steps was 0.52 g/min or 1%. A table of flow variation in the fuel delivery spider is shown in Appendix I. At a branch flow rate of approximately 600 g/min (three times the maximum anticipated), the variation in flow between the highest and lowest branches was 5.5%.

5.3.2 B.C. Research Port Injection Valve

Flow vs valve position is shown in Figure 17. The flow is linear with valve position in two regions, with a gently curved knee between them. The linear regions encompass the assumed idle fuel requirement of 9 g/min and the target maximum flow of 180 g/min. A table of repeatability results appears in Appendix I. The standard deviation in 19 iterations of selecting a low load setting of 25 steps (approximately 26 g/min) was 0.13 g/min or 0.5%.



Flow corrected to 115 psia & 353K

FIGURE 16
GAS FLOW VS VALVE POSITION -
B.C. RESEARCH CENTRAL METERING VALVE

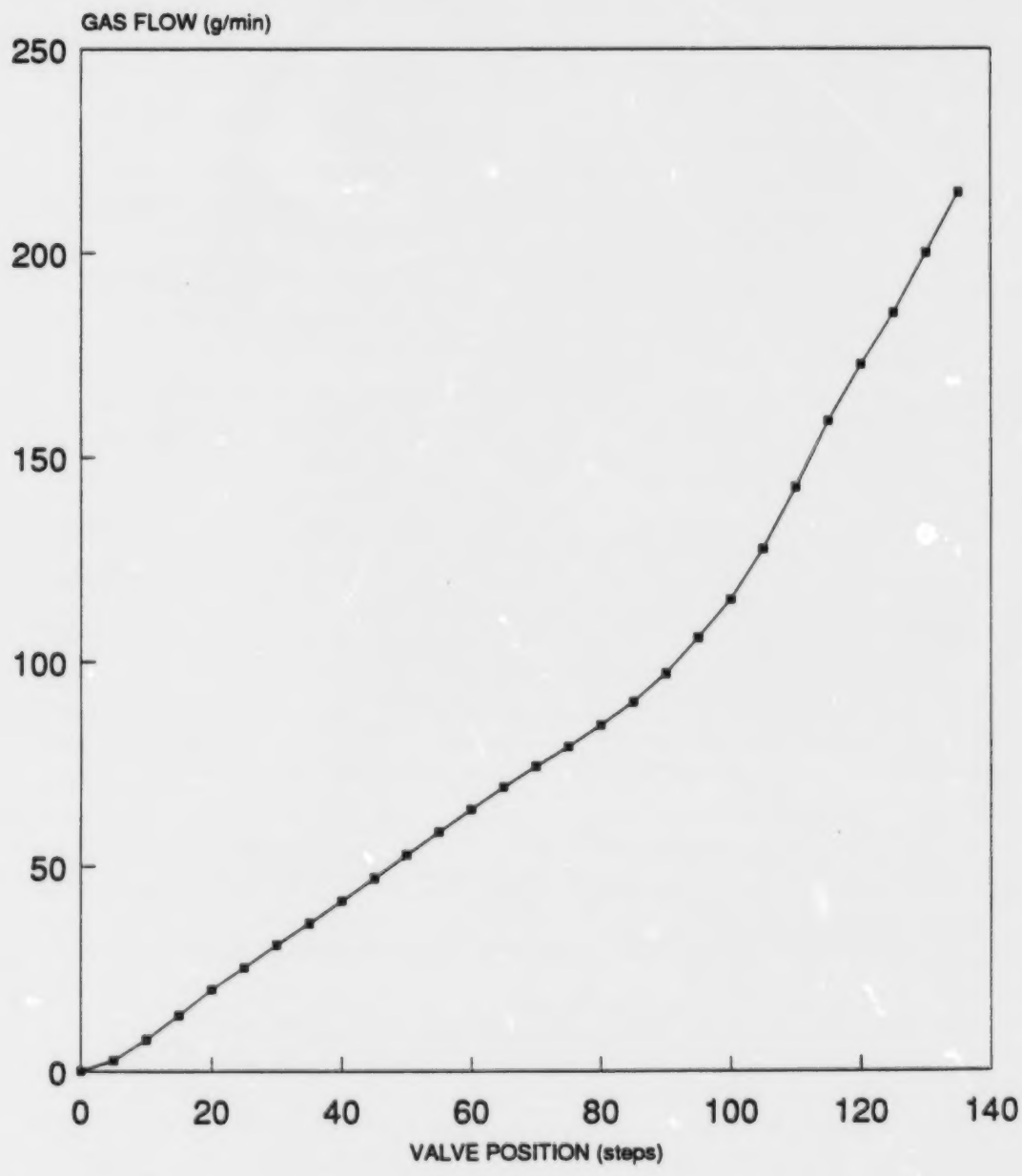
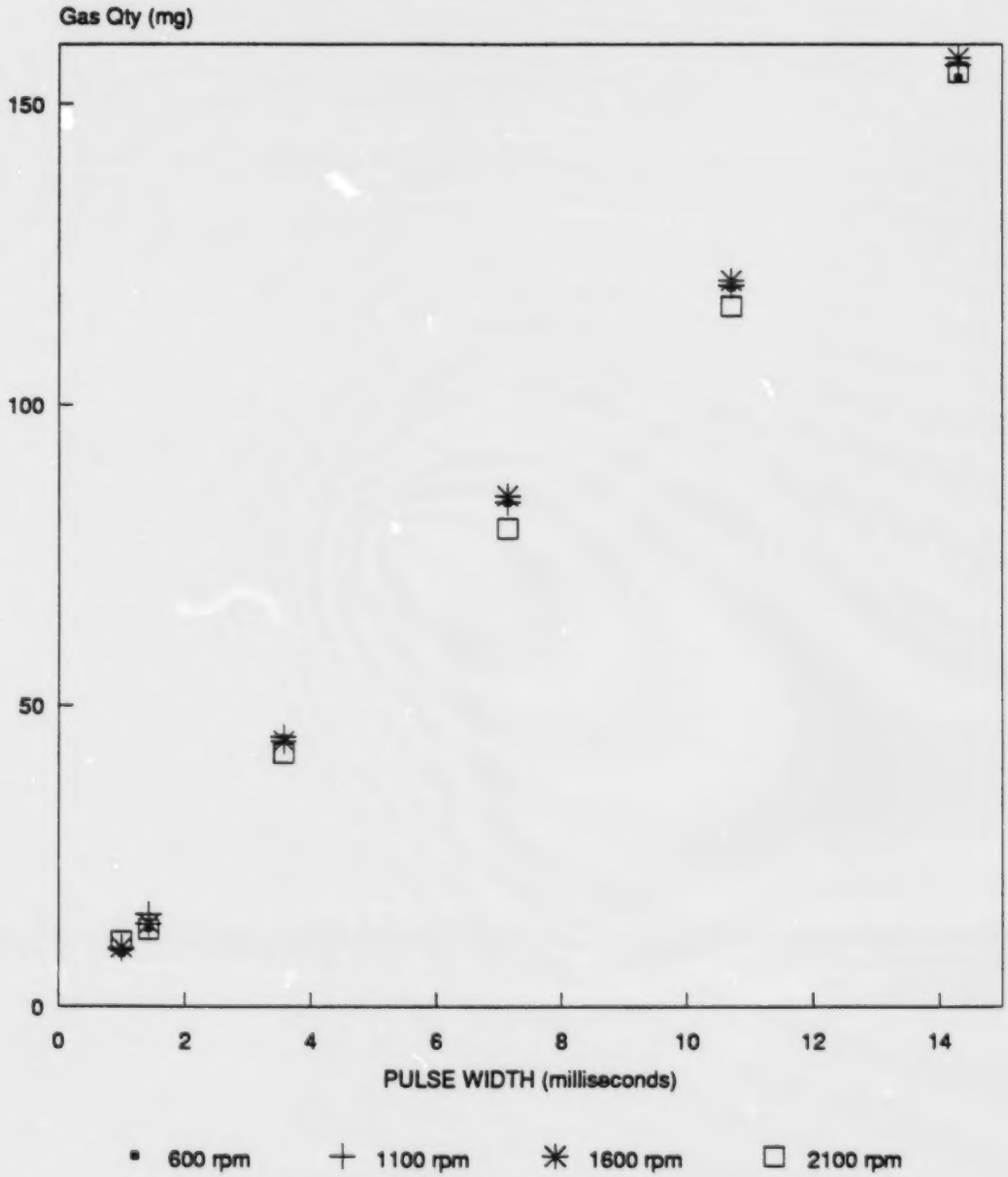


FIGURE 17
GAS FLOW VS VALVE POSITION -
B.C. RESEARCH PORT INJECTION VALVE

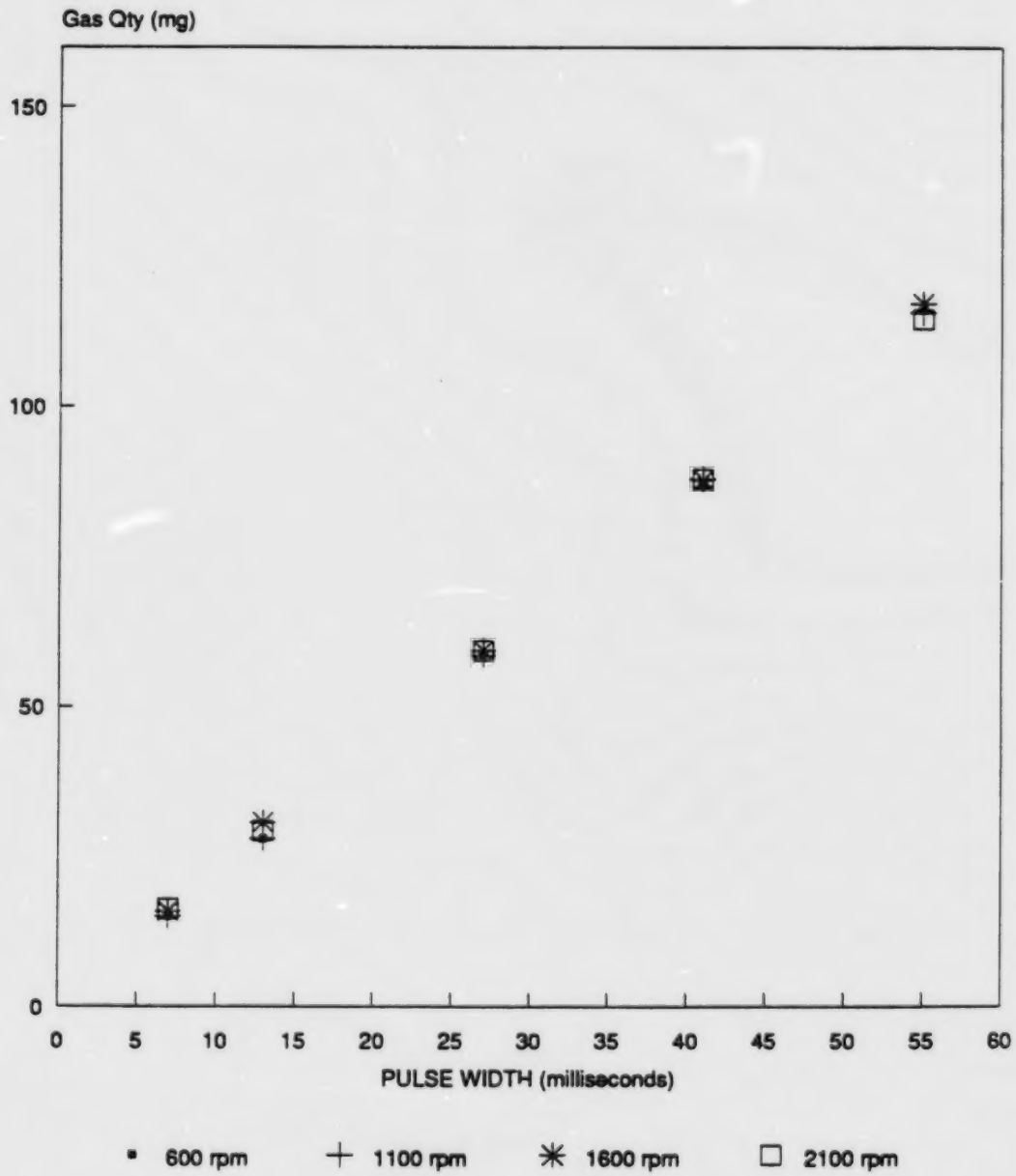
GAS QUANTITY vs PULSE WIDTH
ORTECH SOLENOID OPERATED VALVE



Flows corrected to 115 psia & 353K

FIGURE 18
GAS QUANTITY VS PULSE WIDTH -
ORTECH SOLENOID OPERATED VALVE

GAS QUANTITY vs PULSE WIDTH
SPI HSV3000 SOLENOID OPERATED VALVE



Flows corrected to 115 psia & 353K

FIGURE 19
GAS QUANTITY VS PULSE WIDTH -
SPI HSV3000 SOLENOID OPERATED VALVE

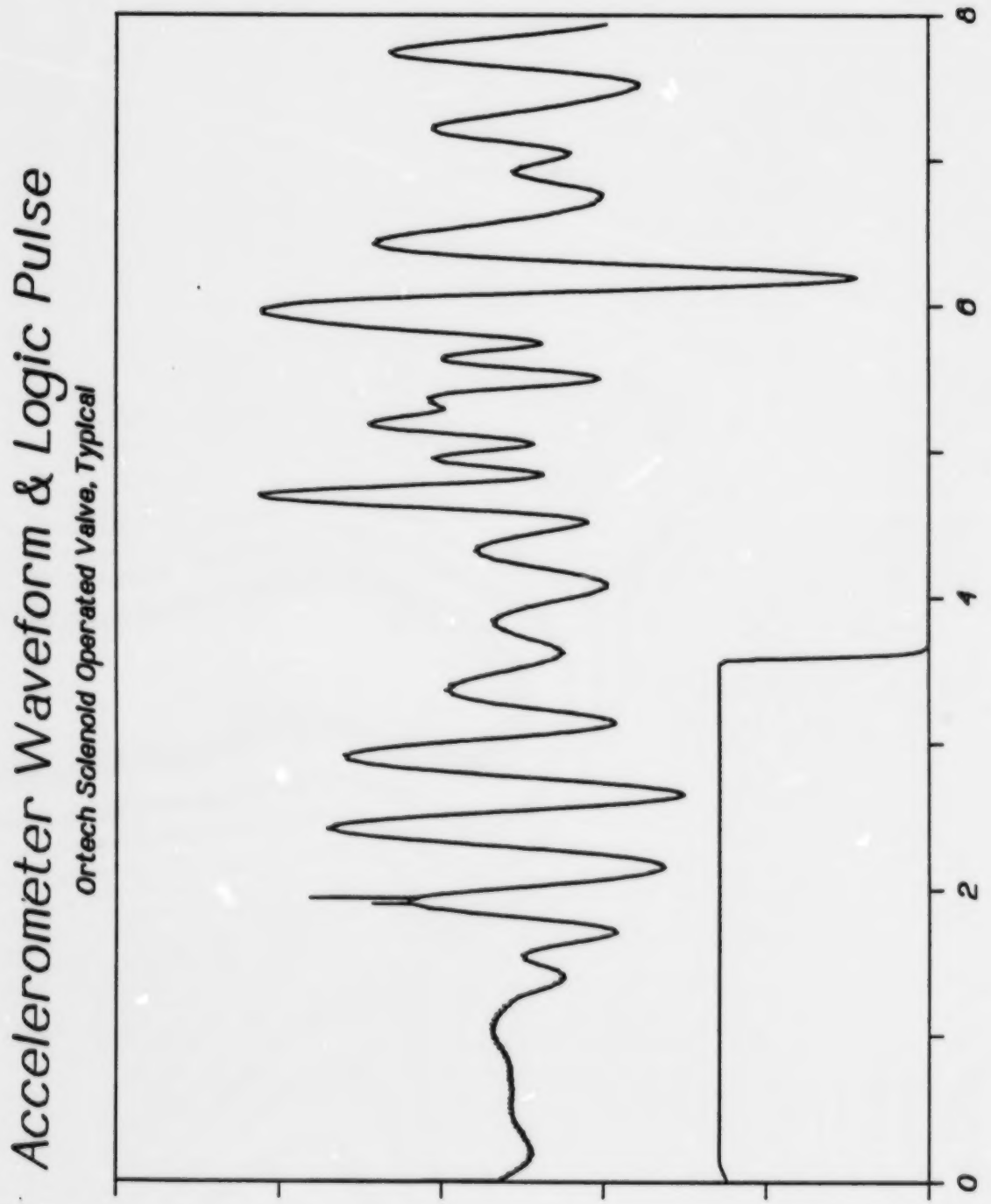


FIGURE 20
ACCELEROMETER WAVEFORM & LOGIC PULSE - ORTECH SOLENOID OPERATED VALVE, TYPICAL

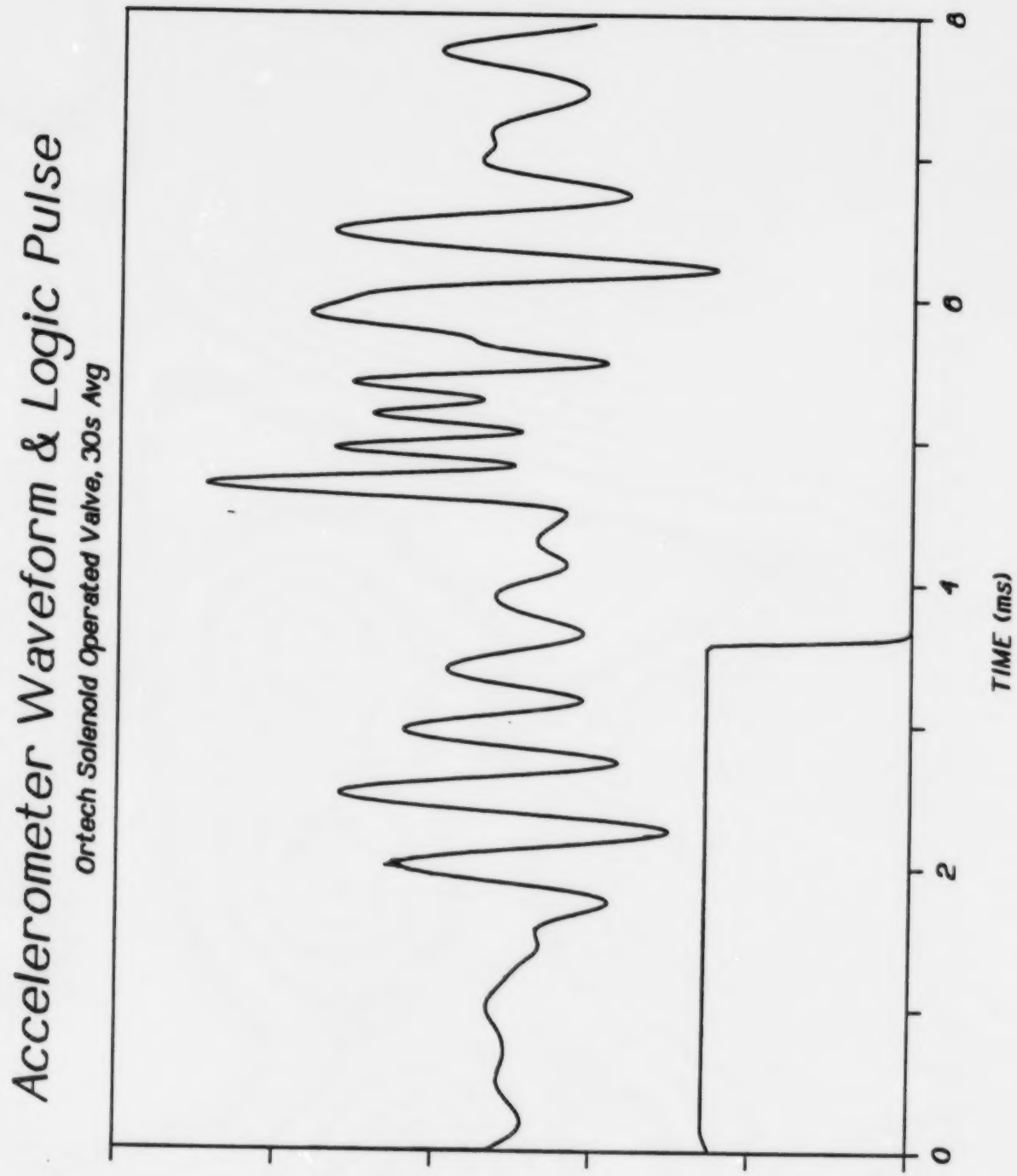


FIGURE 21
ACCELEROMETER WAVEFORM & LOGIC PULSE -
ORTECH SOLENOID OPERATED VALVE, AVERAGE

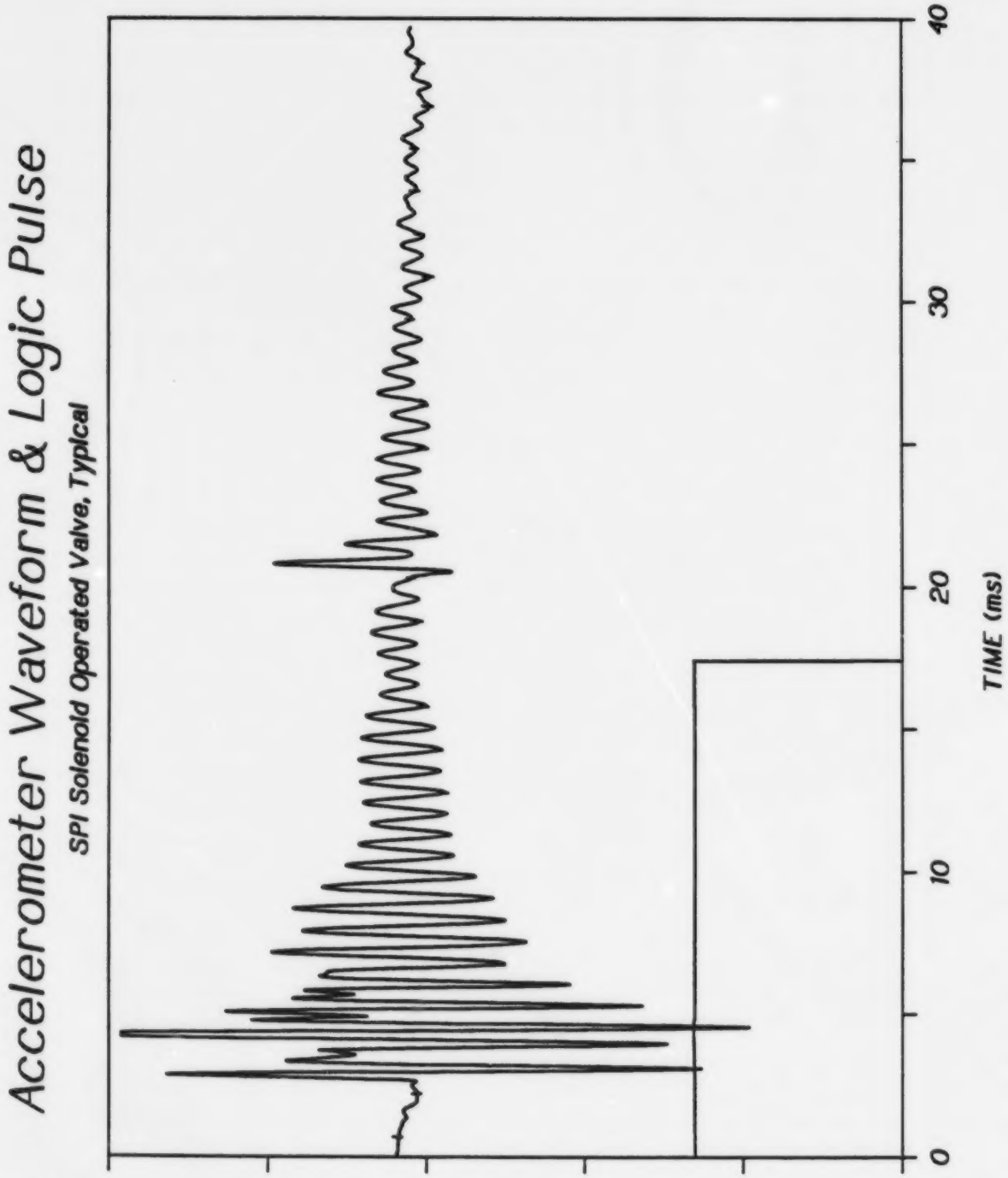


FIGURE 22
ACCELEROMETER WAVEFORM & LOGIC PULSE -
SPI SOLENOID OPERATED VALVE, TYPICAL

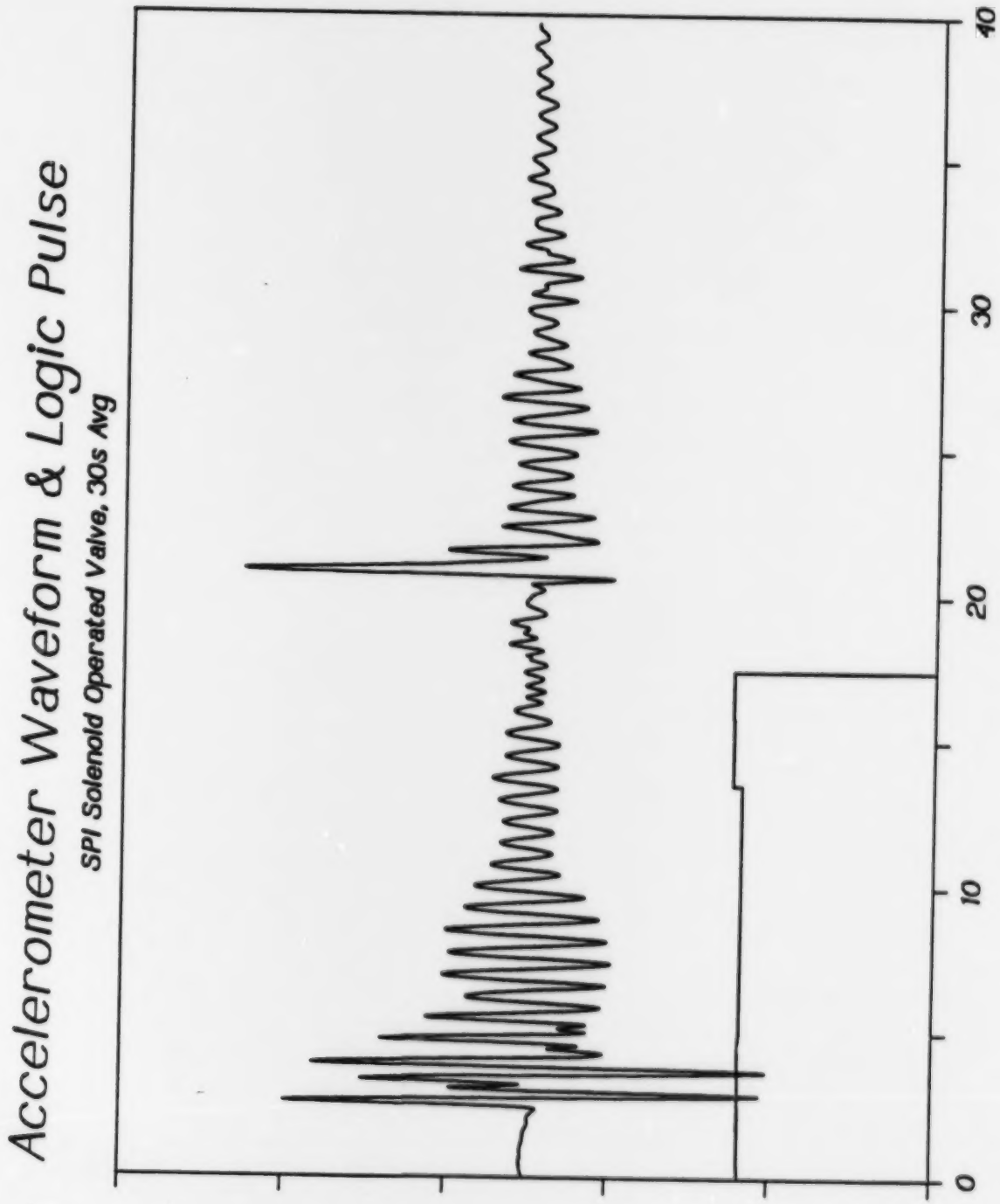


FIGURE 23
ACCELEROMETER WAVEFORM & LOGIC PULSE -
SPI SOLENOID OPERATED VALVE, AVERAGE

5.3.3 Ortech Solenoid Operated Injector

Gas quantity vs pulse width at different rpm is shown Figure 18. The gas quantity is essentially linear with pulse width over the full range, and shows no significant change with rpm. The linear region nearly encompasses the idle fuel requirement of 8.7 mg/cycle, but the target maximum fuel quantity of 175 mg/cycle at a pulse width of 14.3 ms is not reached. The fuel quantity delivered at 14.3 ms is approximately 155 mg. A table of valve open duration repeatability appears in Appendix I. The standard deviation in duration of 19 valve opening and closing events (as inferred from accelerometer traces) at a frequency of 17.5 Hz and a logic pulse width of 3.57 ms was 0.06 ms, or 2.2% of the estimated valve open duration. Sample accelerometer traces appear in Figures 19 and 20. The injector was subjected to approximately 231,000 cycles in endurance testing before failure resulting from a broken armature winding connection.

5.3.4 SPI HSV3000 Solenoid Operated Valve

Gas quantity vs pulse width at different rpm is shown in Figure 21. The flow is essentially linear with pulse width over the full range and shows no significant change with rpm. The linear region appears to extend to the assumed idle fuel quantity of 4.4 mg/cycle. The target maximum fuel requirement of 88 mg/cycle at 55 ms is exceeded. A table of valve open duration repeatability appears in Appendix I. The standard deviation of 19 valve opening and closing events (as inferred from accelerometer traces) at a frequency of 17.5 Hz and a logic pulse width of 17.42 ms was 0.15 ms, or 0.82% of the valve open duration. Sample accelerometer traces appear in Figures 22 and 23. The injector was subjected to approximately 2.4 million cycles in endurance testing, with negligible leakage before and after.

6.0 CONCLUSIONS AND DISCUSSION

Each one of the valves tested would be a viable choice for further development of the commercial port injection system. The SPI HSV 3000 solenoid operated valve and the B.C. Research port injection valve performed particularly well in terms of meeting the requirements set for them.

Testing of the Ortech solenoid operated valve revealed problems typical of a prototype built to exceed existing performance levels. Flow testing could not be carried out with gas heated to approximately 323K, or 30 degrees below engine coolant temperature, due to loss of coil efficiency from excessive heat buildup. The valve performed well when gas temperature was maintained at approximately 293K. The problems of heat and

possibly vibration led to early failure in the endurance test, due to a broken connection to the armature winding. In addition, the Ortech valve had slight leakage past the seat when fully closed. This is not a barrier to application on engines, as a solenoid shut-off valve would probably be used for engine shutdown.

The B.C. Research central metering valve showed some minor problems. At the fully closed setting, a flow of approximately 35 g/min was observed. The stepper motor apparently could not provide quite enough force for positive shut-off. This is not a barrier to application on engines, as a solenoid shut-off valve would probably be used for engine shutdown. The discontinuity in the flow vs position curve may have resulted from the flow bench pressure regulator's inability to maintain desired pressure at the higher flows, i.e. the valve was not the only governing restriction. In the absence of other data, however, the flow region above the discontinuity must be assumed unusable for engine transient operation. The maximum flow rate then becomes 780 g/min, and the scope of engine applications is reduced. The valve manufacturer makes a similar valve with a larger, 1/4" diameter orifice; this valve with the B.C. Research developed actuation system should provide the target flow rate in a linear region. Alternatively, a higher operating pressure could be specified as necessary to achieve the target flow rate. The flow variation between branches of the mock-up spider was quite small, considering that the flow rate at which the data were generated was over three times higher than that needed for engine operations, which would tend to accentuate any differences. A flow variation of 5.5% under these conditions indicates that port fuel injection of natural gas using a central metering valve and fuel delivery spider is a feasible concept.

For future work with these valves, the following should be considered:

(1) Development of the Ortech solenoid operated valve for reliability and control of heat buildup should proceed engine dynamometer testing. In addition, improved driver efficiency would increase chances of eventual commercial acceptance.

(2) The SPI HSV3000 valve an apparently trouble-free production valve. In application to the larger engines, there is a choice between a large number of valves (2 per cylinder) and lower fuel utilisation (higher operating pressure). Timed injection is a possibility with still higher pressure or more valves per cylinder.

(3) Application of the B.C. Research port injection valve appears to be straightforward. Each valve would be plumbed to a high pressure fuel plenum and controlled from a central device.

(4) Application of the B.C. Research central metering valve would require design and construction of a fuel delivery spider that fits into the available space around the engine and provides acceptable fuel distribution. Given a satisfactory spider, this system has the advantages of fewer moving parts than any other, and metering to all cylinders controlled at one location.

(5) Although test conditions were controlled and results were corrected to standard conditions, the hardware for providing constant gas conditions in a dynamometer cell or engine bay does not exist, particularly with regard to pressure regulators. Any engine fuel delivery system must be able to maintain accurate control of fuel quantity under a certain amount of variation in gas temperature and pressure. This problem, and that of accomodating the engine's needs under transient conditions, must be considered in application of any of these valves.

REFERENCES

1. MacCarley, C.A. and W.D. Van Vorst 1978. "Electronic Fuel Injection Techniques for Hydrogen Powered I.C. Engines". Proc. Second World Hydrogen Energy Conference, Zurich, Switzerland:2747-2792.

2. MacCarley, C.A. 1980. "Development of a High Speed Injection Valve for Electronic Hydrogen Fuel Injection". Proc. Advances in Hydrogen Energy 2 2:1119-1133.

3. Welch, A.B. and J.S. Wallace 1987. "Development of a Hydrogen Injector for use in Hydrogen-Fueled Diesel Engine Research". Proc. 21st Intersociety Energy Conversion Conference:2110-2115.

4. Beck, N.J., et al. 1989. "Electronic Fuel Injection for Dual Fuel Diesel Methane". SAE Technical Paper No. 891652.

5. Miele, D., T. Krepec and T. Giannacopoulos, "Electronic Injection System for Natural Gas in a Diesel Engine - Development and Testing", SAE Paper No. 890852 (1989).

6. Homan, H.S., R.K. Reynolds, P.C.T. de Hoer and W.J. McLean, "Hydrogen-Fueled Diesel Engine without Timed Ignition", Int. J. Hydrogen Energy, 4, 315-325 (1979).

7. Furuhama S. and Y. Kobayashi, "Development of a Hot Surface Ignition Hydrogen Injection Two-Stroke Engine", Int. J. Hydrogen Energy, 9, 205-213 (1984).

8. Murray, R.G., R.J. Schoeppel and C.L. Gray, "The Hydrogen Engine in Perspective", Proc. Seventh Intersociety Energy Conversion Engineering Conference, ASC, Washington, D.C., 1375-1391 (1972).

9. Ikegami N., K. Miwa and M. Shoiji, "A Study on Hydrogen-Fueled Compression Ignition Engines", Proc. Third World Hydrogen Energy Conference, Vol. 3, Pergamon Press, Oxford, 969-983 (1980).

10. Swain M.R., J.M. Pappas, R.R. Adt, Jr. and W.J.D. Escher, "Hydrogen Engine Design Data Base Summary", Proc 19th Intersociety Energy Conversion Engineering Conference. See also the excellent and thorough contract report: "Experiment Hydrogen-Fueld Automotive Engine Design Data Base Project", DOE/CS/31212-1, May, 1983.

11. Furuhama S. and T. Fukuma, "High Output Power Hydrogen Engine with High Pressure Fuel Injection, Hot Surface Ignition and Turbocharging", Proc. Fifth World Hydrogen Energy Converence, Vol. 4, Pergamon Press, Oxford, 1493-1504 (1984).

12. Welch A.B. and J.S. Wallace, "Performance Characteristics of a Hydrogen-Fueled Diesel Engine with Ignition Assist", Final Report to the National Research Council of Canada, March 1986.

13. Welch A.B. and J.S. Wallace, "Development of a Hydrogen Injector for Use in Hydrogen-Fueled Diesel Engine Research", Proc. 21st Intersociety Energy Conversion Engineering Conference, ACS, Washington, D.C., 2110-2115 (1987).

14. Welch A. and L. Austin, "Natural Gas Detroit Diesel 2-Cycle Engine" Fifth Windsor Workshop on Alternative Fuels, Windsor, Ontario, June 12-14, (1989).

15. Seilly A.H., "Helenoid Actuators = A New Concept in Extremely Fast Acting Solenoids", SAE Paper No. 790119 (1979).

16. Seilly, A.H., "Colenoid Actuators = Further Developments in Extremely Fast Acting Solenoids", SAE Paper No. 810462 (1981).

17. Schechter M.M., "Fast Response Multipole Solenoids", SAE Paper No. 830202 (1983).

18. Personal Communication, Prof. P.P. Biringer, Department of Electrical Engineering, University of Toronto.

19. Wolber W., SAE Paper No. 840306.

20. Smith R.J., "Circuit Devices and Systems", Fourth Edition, John Wiley and Sons, New York, 636-649 (1984).

21. Dolza, J., et al, "The General Motors Fuel Injection System", SAE Transactions, Volume 65, 739-757 (1957).

22. Winkler, A.H, and R.W Sutton, "Electrojector - Bendix Electronic Fuel Injection System", SAE Transactions, Volume 65, 759-765 (1957)

APPENDIX I - TABLES

Heavy Duty Engine Fuel Requirements

Valve Specifications

B.C. Research Central Metering Valve

B.C. Research Port Injection Valve

Ortech Solenoid Operated Valve

SPI HSV 3000 Solenoid Operated Valve

Position/Flow Repeatability - B.C. Research Central Metering Valve

Position/Flow Repeatability - B.C. Research Port Injection Valve

Repeatability of Open Duration - Ortech Solenoid Operated Valve

Repeatability of Open Duration - SPI Solenoid Operated Valve

Branch Flow Variations in Fuel Delivery Spider

HEAVY DUTY ENGINE FUEL REQUIREMENTS

Engine	Power	Rated Speed	No. of Cyl.	Power per Cyl.	Max. Air-flow	Max. available time for injection pulse at rated speed	
						Timed	Untimed
	(HP)	(RPM)				(ms)	(ms)
DDC 8v92	475	2100	8	59	NA	7.1	28.6
Cummins NTC 400	400	2100	6	67	NA	14.3	57.1
Cummins L10	300	2100	6	50	NA	14.3	57.1
Cat 3406	425	2100	6	71	NA	14.3	57.1
Cat 3306	300	2200	6	50	NA	13.6	54.5
Cat 3208	210	2800	8	26	NA	10.7	42.9

Engine	Fuel req. per cyl. @ rated speed, full load & 0.35 eff'y	Fuel per cycle @ full load	Fuel mass flow @ rated speed	
			Timed	Untimed
	(kg/min)	(g)	(g/sec)	(g/sec)
DDC 8v92	0.153	0.0730	10.23	2.556
Cummins NTC 400	0.172	0.1640	11.48	2.870
Cummins L10	0.129	0.1230	8.61	2.153
Cat 3406	0.183	0.1743	12.20	3.050
Cat 3306	0.129	0.1174	8.61	2.153
Cat 3208	0.068	0.0484	4.52	1.130

Engine	Manifold pressure (absolute)	Injection pressure (absolute)	Gas density @ injection pressure &293K	Injector Volumetric Flow Capacity	
				Timed	Untimed
	(bar)	(bar)	(kg/m3)	(m3/min)	(m3/min)
DDC 8v92	2.75	5.06	3.32	0.1849	0.0462
Cummins NTC 400	2.75	5.06	3.32	0.2076	0.0519
Cummins L10	2.75	5.06	3.32	0.1557	0.0389
Cat 3406	2.75	5.06	3.32	0.2206	0.0552
Cat 3306	2.75	5.06	3.32	0.1557	0.0389
Cat 3208	2.75	5.06	3.32	0.0818	0.0204

VALVE SPECIFICATIONS

B.C. Research Central Metering Valve

Valve Type	Rising Plug
Orifice Size	3/16" (4.76mm)
Control Resolution	135 steps
Actuation Speed	250 steps/sec
Maximum Flow Rate @ 115 psia & 353K	960 g/min.
Dimensions (mm)	25 x 75 x 65

B.C. Research Port Injection Valve

Valve Type	Needle
Orifice Size	0.093" (2.4mm)
Control Resolution	135 steps
Actuation Speed	300 steps/sec
Maximum Flow Rate @ 115 psia & 353K	220 g/min
Dimensions (mm)	20 x 50 x 60

Ortech Solenoid Operated Valve

Valve Type	Poppet
Lift	0.018" (0.46mm)
Frequency	0 - 17.5 Hz
Pulse Width	1 - 14.3 ms
Maximum Fuel Quantity @ 115 psia & 353K	155 mg
Dimensions (mm)	60 ϕ x 90

SPI HSV3000 Solenoid Operated Valve

Valve Type	Spool
Frequency	0 - 17.5 Hz
Pulse Width	2 - 55 ms
Maximum Fuel Quantity @ 115 psia & 353K	120 mg
Dimensions (mm)	40 ϕ x 75

POSITION/FLOW REPEATABILITY
BC RECEARCH CENTRAL METERING VALVE

Data from 22 cycles from
full open to 25 steps:

Iteration	Command (step #)	Flow (g/min)
1	24	51.79
2	24	51.46
3	24	52.08
4	24	52.27
5	24	51.87
6	24	52.28
7	24	52.30
8	24	52.04
9	24	52.23
10	24	52.03
11	24	51.74
12	24	52.00
13	24	51.98
14	24	51.72
15	24	51.75
16	24	51.55
17	24	51.53
18	24	51.07
19	24	50.75
20	24	50.80
21	24	50.91
22	24	50.54

STATISTICAL ANALYSIS OF FLOW
(VALVE POSITIONING) ACCURACY:

Driver Step Rate: 250 Hz

Position Command: Step 24

Avg Flow (g/min): 51.67

Std Dev (g/min): 0.52

Std Dev (%): 1.0%

POSITION/FLOW REPEATABILITY
BC RECEARCH PORT INJECTION VALVE

Data from 19 cycles from
full open to 25 steps:

Iteration	Command (step #)	Flow (g/min)
1	25	25.90
2	25	25.98
3	25	25.92
4	25	25.89
5	25	25.92
6	25	25.77
7	25	25.74
8	25	25.75
9	25	25.62
10	25	25.79
11	25	25.65
12	25	25.52
13	25	25.69
14	25	25.73
15	25	25.67
16	25	25.54
17	25	25.65
18	25	25.64
19	25	25.70

STATISTICAL ANALYSIS OF FLOW
(VALVE POSITIONING) ACCURACY:

Driver Step Rate:	300 Hz
Position Command:	Step 25
Avg Flow (g/min):	25.74
Std Dev (g/min):	0.13
Std Dev (%):	0.5%

REPEATABILITY OF VALVE OPEN DURATION
ORTECH SOLENOID OPERATED VALVE

DATA FROM 19 ACCELEROMETER TRACES OF
VALVE RESPONSE TO 3.57ms LOGIC PULSE
STARTING AT 0ms, ENDING AT 3.57ms

STATISTICAL ANALYSIS
BASED ON 3.57ms PULSE:

Avg Dur (ms):	2.92
Std Dev (ms):	0.06
Std Dev (%):	2.22%

Trace No.	Valve open (ms)	Valve close (ms)	Duration (ms)	Error in Duration (ms)
1	1.78	4.73	2.95	-0.03
2	1.85	4.70	2.85	0.07
3	1.91	4.73	2.82	0.10
4	1.81	4.73	2.92	0.00
5	1.90	4.72	2.82	0.10
6	1.82	4.70	2.88	0.04
7	1.86	4.69	2.83	0.09
8	1.84	4.69	2.85	0.07
9	1.80	4.68	2.88	0.04
10	1.76	4.69	2.93	-0.01
11	1.77	4.69	2.92	0.00
12	1.73	4.69	2.96	-0.04
13	1.67	4.69	3.02	-0.10
14	1.72	4.70	2.98	-0.06
15	1.66	4.70	3.04	-0.12
16	1.74	4.68	2.94	-0.02
17	1.72	4.69	2.97	-0.05
18	1.75	4.67	2.92	0.00
19	1.71	4.70	2.99	-0.07

REPEATABILITY OF VALVE OPEN DURATION
SPI HSV3000 SOLENOID OPERATED VALVE

DATA FROM 19 ACCELEROMETER TRACES OF
VALVE RESPONSE TO 17.42ms LOGIC PULSE
STARTING AT 0ms, ENDING AT 17.42ms

STATISTICAL ANALYSIS
BASED ON 17.42ms PULSE:

Avg Dur (ms):	17.84
Std Dev (ms):	0.15
Std Dev (%):	0.82%

Trace No.	Valve open (ms)	Valve close (ms)	Duration (ms)	Error in Duration (ms)
1	2.58	20.57	17.99	-0.05
2	2.68	20.55	17.87	0.07
3	2.89	20.57	17.68	0.26
4	2.58	20.57	17.99	-0.05
5	2.58	20.58	18.00	-0.06
6	2.88	20.52	17.64	0.30
7	2.68	20.58	17.90	0.04
8	2.59	20.58	17.99	-0.05
9	2.93	20.56	17.63	0.31
10	2.61	20.56	17.95	-0.01
11	2.60	20.57	17.97	-0.03
12	2.69	20.56	17.87	0.07
13	2.70	20.54	17.84	0.10
14	2.60	20.56	17.96	-0.02
15	2.96	20.56	17.60	0.34
16	2.96	20.56	17.60	0.34
17	2.68	20.56	17.88	0.06
18	2.59	20.55	17.96	-0.02
19	2.86	20.54	17.68	0.26
Avg'd Trace	2.62	20.56	17.94	

FLOW VARIATION IN FUEL DELIVERY SPIDER

Gas flow corrected
to 115 psia, 353K:

Branch	Flow (g/min)
1	621.0
2	602.5
3	602.2
4	588.0
5	607.4
6	598.9

STATISTICAL ANALYSIS:

Highest	621.0
Lowest:	588.0
Variation:	5.5%

APPENDIX II - ENGINEERING DRAWINGS

Continuous Flow Valve Drawings:

- Adapter - Stepper to Large Valve
- Adapter - Stepper to Small Valve

Fuel Delivery Spider Drawings:

- Fuel Manifold
- No. 1 & 6 Cyl. Fuel Line
- No. 2 Cyl. Fuel Line
- No. 3 Cyl. Fuel Line
- No. 4 Cyl. Fuel Line
- No. 5 Cyl. Fuel Line
- No. 6 Cyl. Fuel Line
- Fuel Spider Assembly

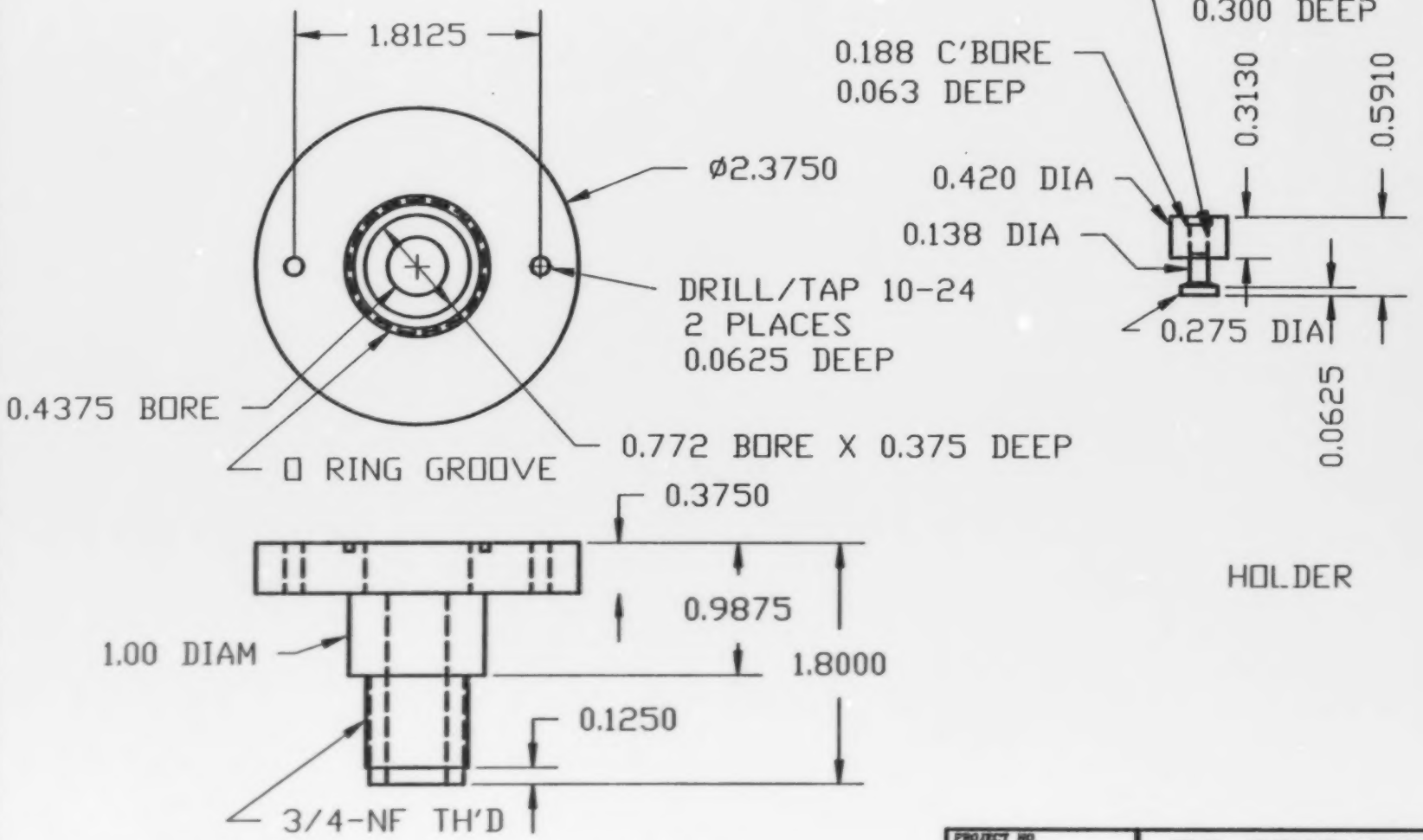
Test Bench Drawings:

- Valve Mounting Fixture
- Mounting Brackets & Ass'y

Ortech Valve Drawings:

- Gas Injector
- Injector Body
- Pintle/Armature
- Injector Head
- Injector Cap
- Coil Bobbin

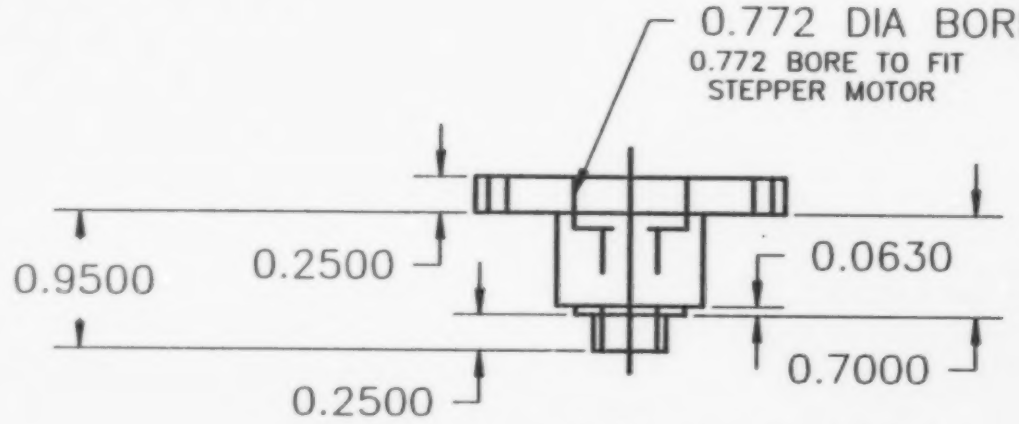
ADAPTOR



HOLDER

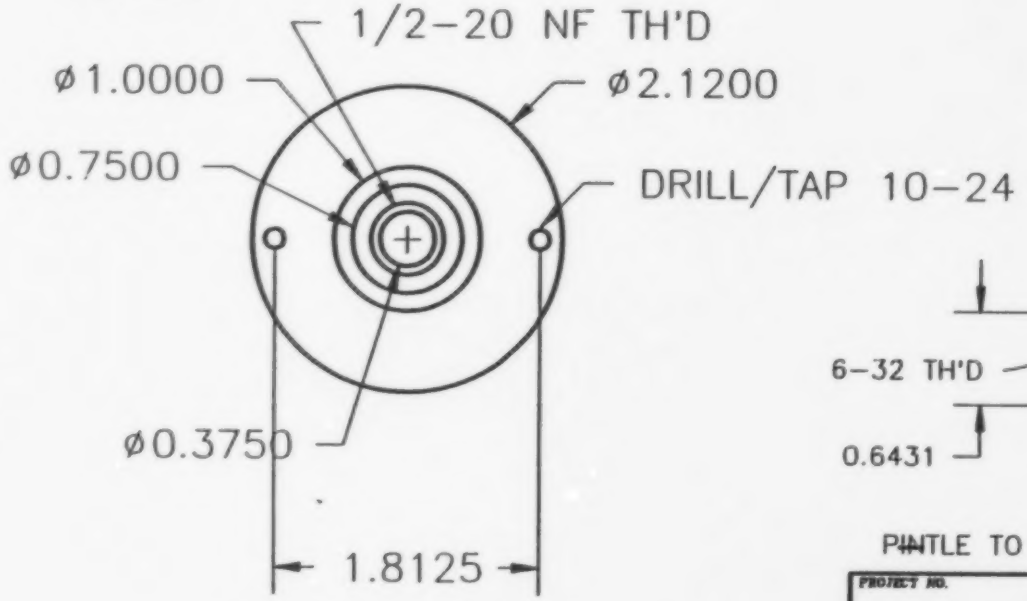
NOTES
MAT'L 6061 T6

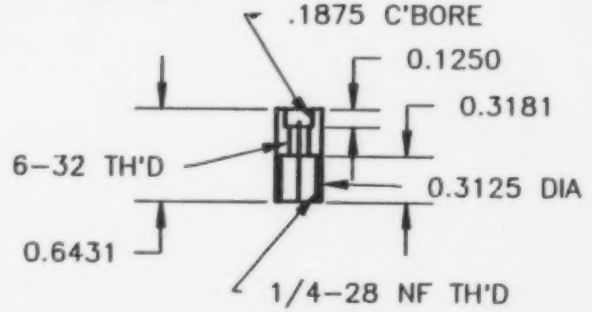
PROJECT NO. 6-05-973			BC RESEARCH
DRAWN	CP	JAN 90	PROJECT GAS VALVE
CHECKED			
CAD REF	PLUGVD		TITLE ADAPTOR – STEPPER TO LARGE VALVE
SHEET 1 OF 1			
SCALE NONE			DWG NO 6-05-973-2 REV 0



NOTES

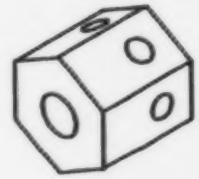
MATL: ALUM 6061 T6
CUT VALVE PINTLE THREAD
TO 0.3125 LONG

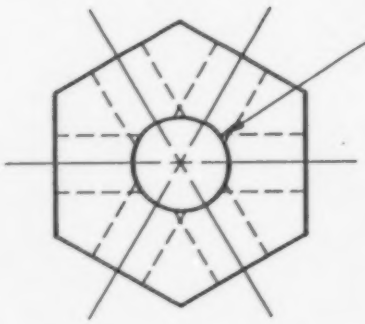


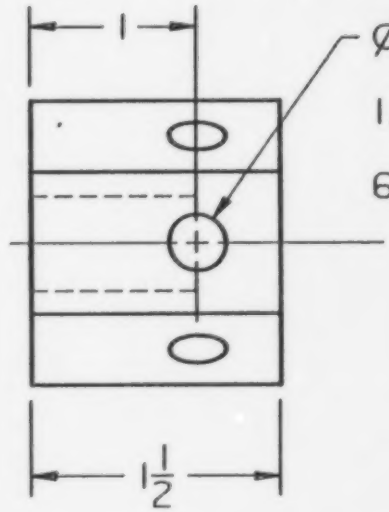


PINTLE TO STEPPER ADAPTOR

PROJECT NO.	
DRAWN	
C LED	
SCALE	







MAT'L: 1-1/2 BRASS HEX. STOCK

REV.	DESCRIPTION	DATE

NO.	DESCRIPTION	QTY.

DRAWN G.V.H.
SCALE 1:1
DATE SEPT. 29/89

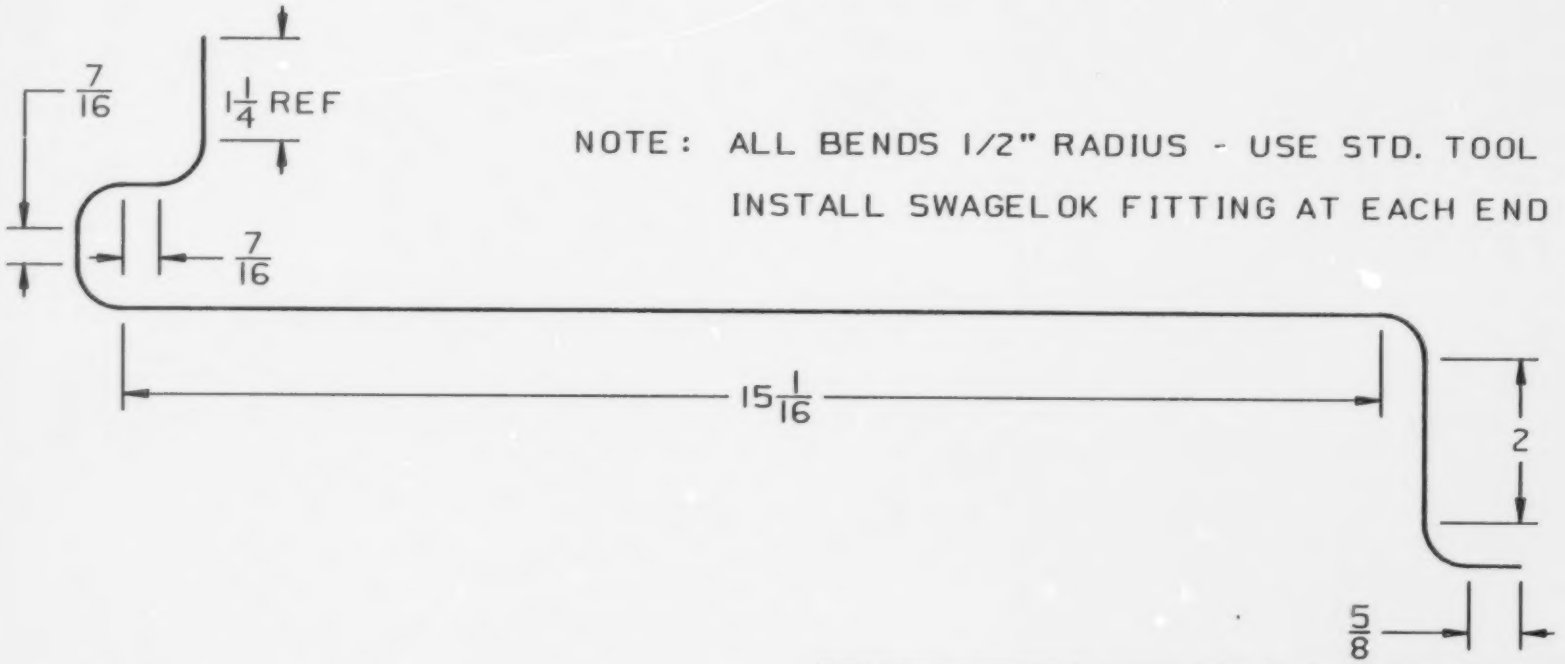
BC RESEARCH

TITLE: FUEL MANIFOLD

DWG.NO. 605973-001

SIZE A

NOTE: 2 REQ'D



NOTE: ALL BENDS 1/2" RADIUS - USE STD. TOOL

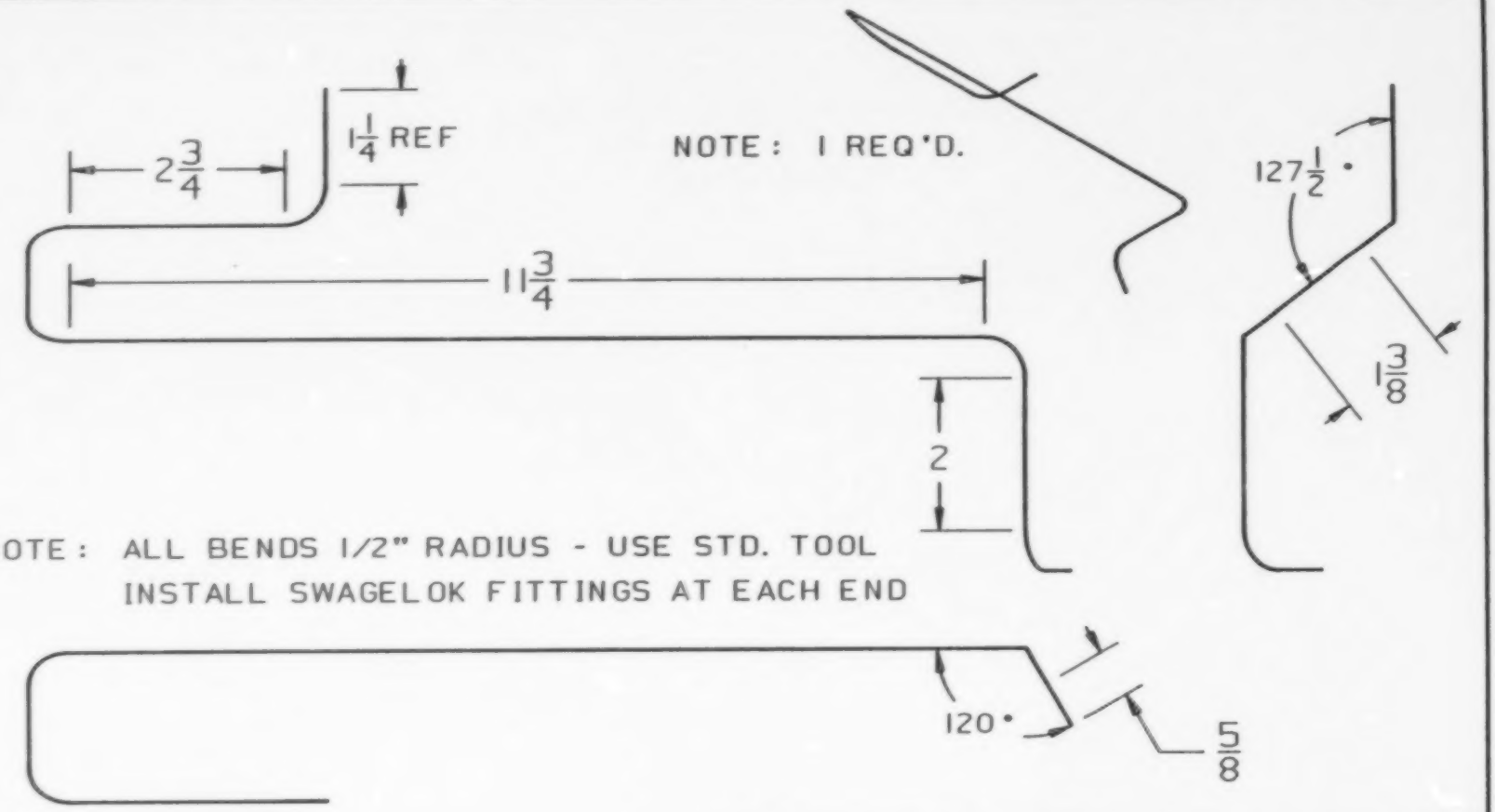
INSTALL SWAGELOK FITTING AT EACH END

MAT'L: 1/4" .035 WALL SS TUBING

24" LONG - DO NOT TRIM

NO.	DESCRIPTION	QTY.
DRAWN	G.V.H.	BC RESEARCH
SCALE	1:2	
DATE	OCT. 3/89	
TITLE	NO. 1 & 6 CYL. FUEL LINE	
DWG.NO.	605973-002	SIZE A

REV.	DESCRIPTION	DATE



NOTE: ALL BENDS 1/2" RADIUS - USE STD. TOOL
INSTALL SWAGELOK FITTINGS AT EACH END

MAT'L: 1/4" .035 WALL SS TUBING
24" LONG - DO NOT TRIM

NO.	DESCRIPTION	QTY.

DRAWN	G.V.H.
SCALE	1:2
DATE	OCT. 4/89

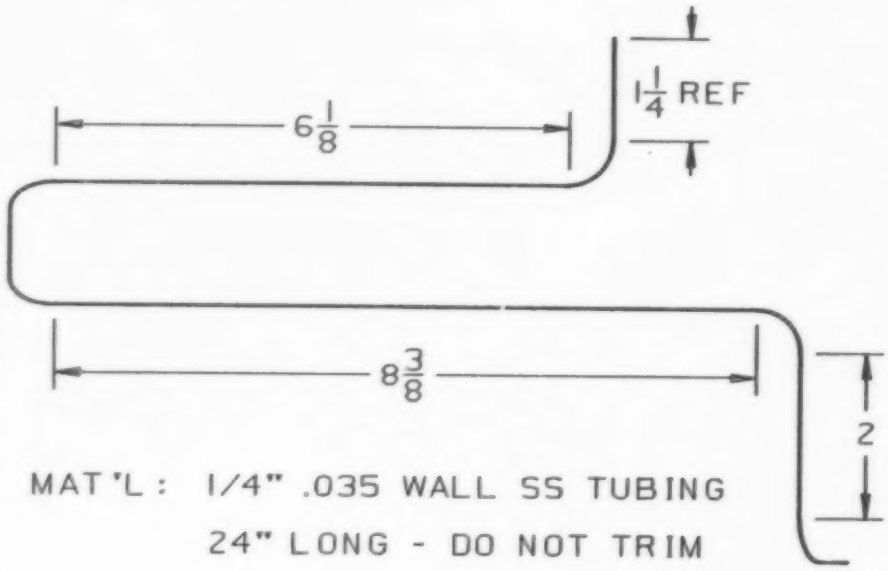
BC RESEARCH

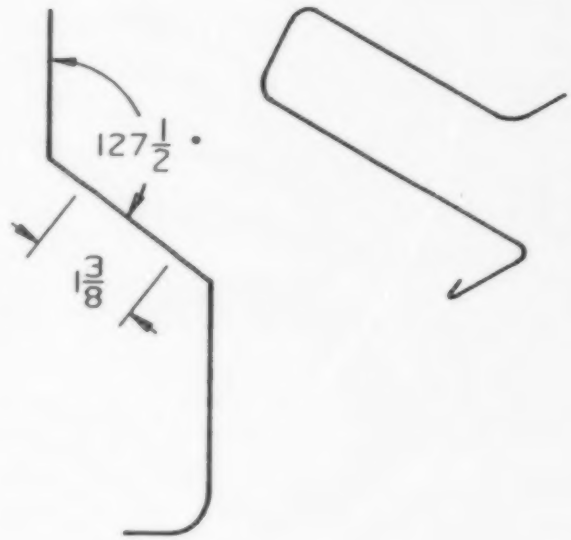
TITLE: NO. 2 CYL. FUEL LINE

DWG.NO. 605973-003

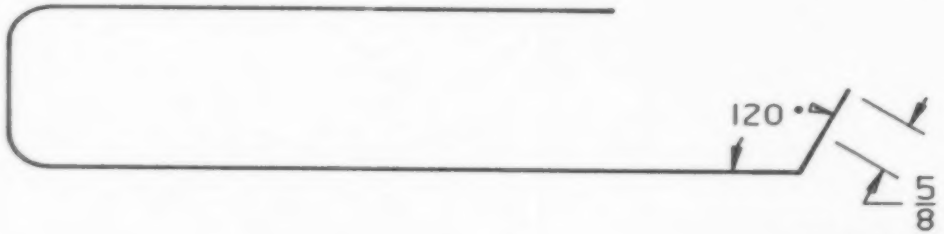
SIZE A

REV.	DESCRIPTION	DATE





MAT'L: 1/4" .035 WALL SS TUBING
24" LONG - DO NOT TRIM



NOTE: 1 REQ'D.

NOTE: ALL BENDS 1/2" RADIUS
USE STD. TOOL
INSTALL SWAGELOK FITTING
AT EACH END

REV.	DESCRIPTION	DATE

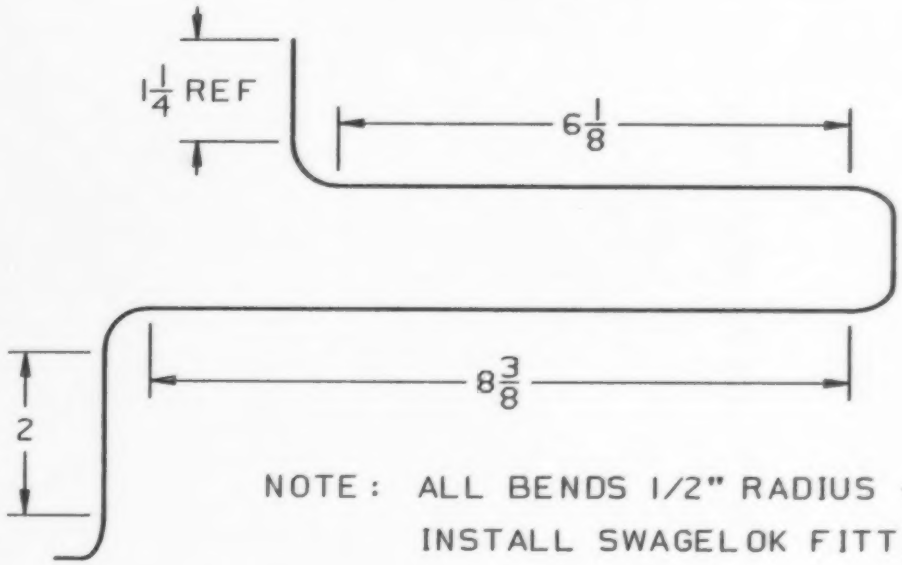
NO.	DESCRIPTION	QTY.
DRAWN	G.V.H.	
SCALE	1:2	
DATE	OCT. 4/89	

BC RESEARCH

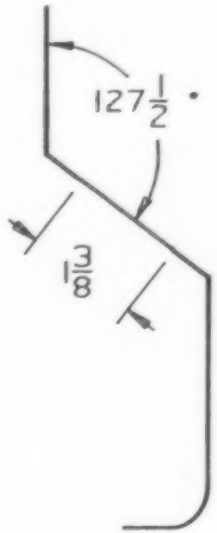
TITLE: NO. 3 CYL. FUEL LINE

DWG.NO. 605973-004

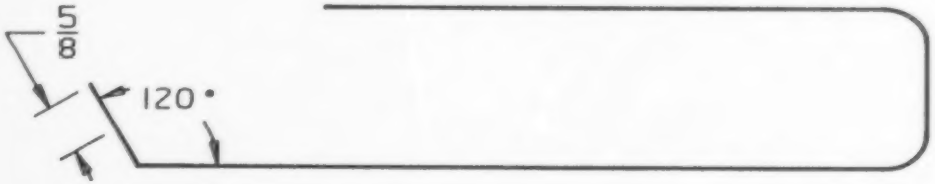
SIZE A

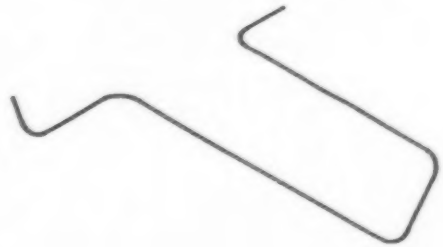


NOTE: 1 REQ'D.



NOTE: ALL BENDS 1/2" RADIUS - USE STD. TOOL
INSTALL SWAGELOK FITTING AT EACH END



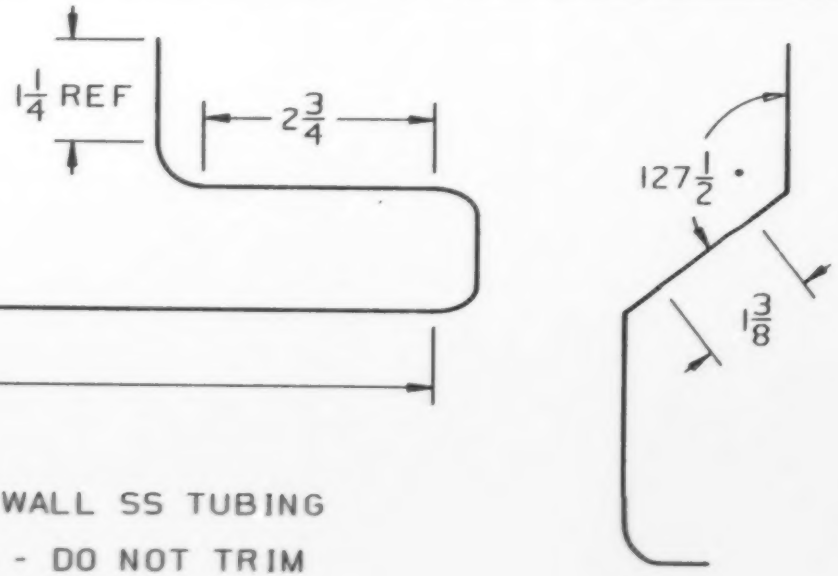


MAT'L: 1/4" .035 WALL SS TUBING
24" LONG - DO NOT TRIM

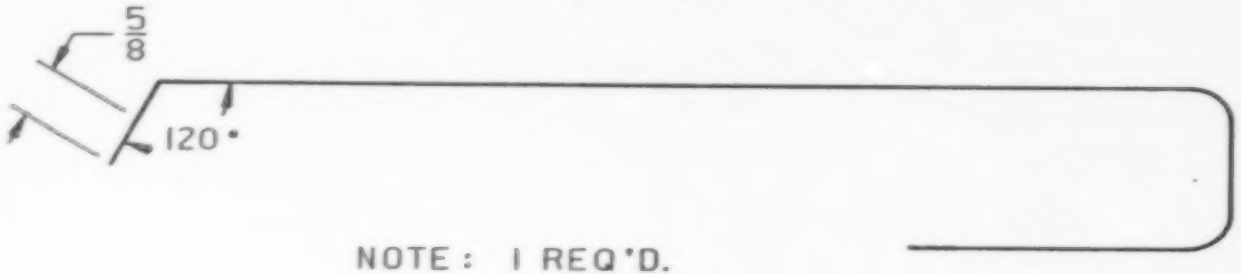
REV.	DESCRIPTION	DATE

NO.	DESCRIPTION	QTY.
DRAWN	G.V.H.	BC RESEARCH
SCALE	1:2	
DATE	OCT. 4/89	
TITLE	NO. 4 CYL. FUEL LINE	
DWG.NO.	605973-005	SIZE A

NOTE: ALL BENDS 1/2" RADIUS
USE STD. TOOL
INSTALL SWAGELOK FITTING
AT EACH END



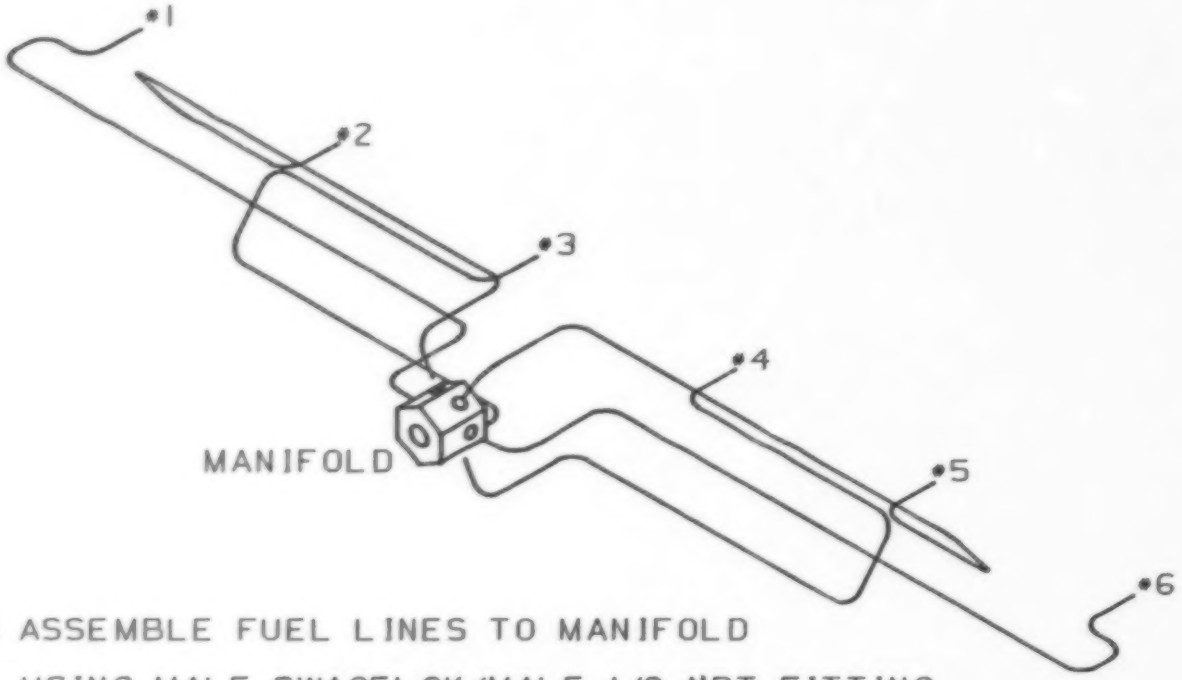
MAT'L: 1/2" .035 WALL SS TUBING
24" LONG - DO NOT TRIM



NOTE: 1 REQ'D.

NO.	DESCRIPTION	QTY.
DRAWN	G.V.H	BC RESEARCH
SCALE	1:2	
DATE	OCT. 4/89	
TITLE	NO. 5 CYL. FUEL LINE	
DWG.NO.	605973-006	SIZE A

REV.	DESCRIPTION	DATE



NOTE: ASSEMBLE FUEL LINES TO MANIFOLD
USING MALE SWAGELOK/MALE 1/8 NPT FITTING

NO.	DESCRIPTION	QTY.

DRAWN	GVH
SCALE	NONE
DATE	OCT. 4/89

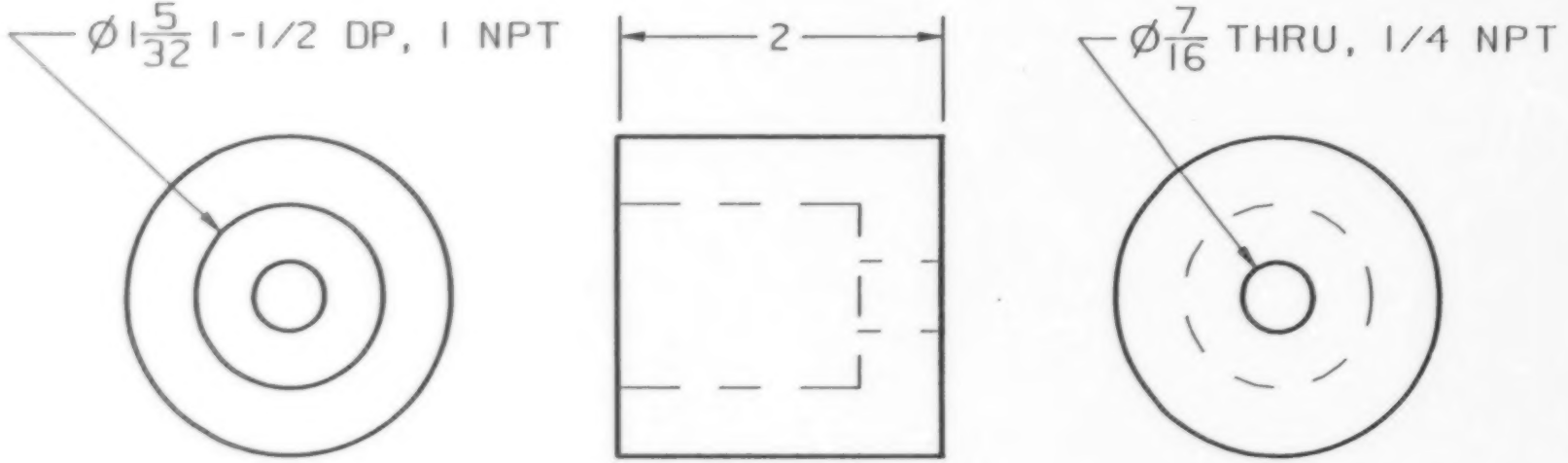
BC RESEARCH

TITLE: FUEL SPIDER ASSEMBLY

DWG.NO. 605973-007

SIZE A

REV.	DESCRIPTION	DATE

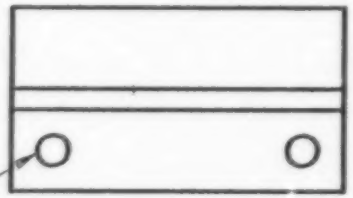


MAT'L: 2" AL. ROUND STOCK

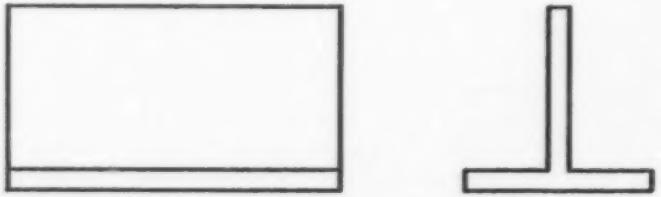
NO.	DESCRIPTION	QTY.
DRAWN	GVH	BC RESEARCH
SCALE	1:1	
DATE	OCT. 6/89	
TITLE	VALVE MOUNTING FIXTURE	
DWG.NO.	605973-008	SIZE A

REV.	DESCRIPTION	DATE

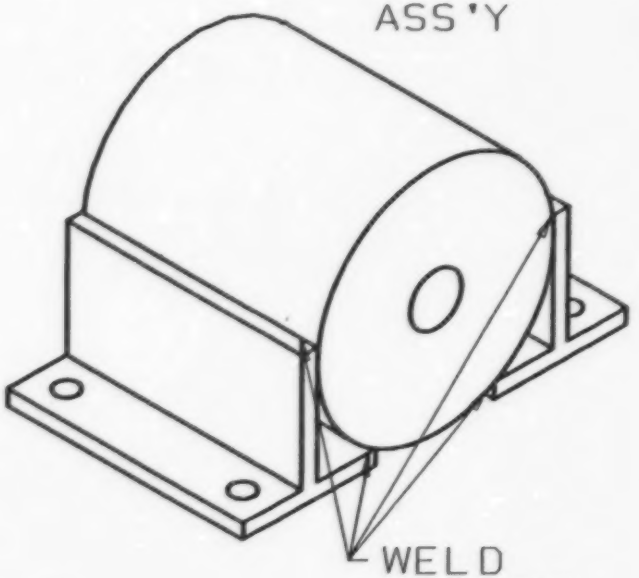
MOUNTING BRACKET - 2 REQ'D



MOUNTING HOLES - TO SUIT



ASS'Y



WELD
TO SUIT

MAT'L : 1-1/4X1-1/4 AL. TEE

NO.	DESCRIPTION	QTY.

DRAWN	GVH
SCALE	1:1
DATE	OCT. 6/89

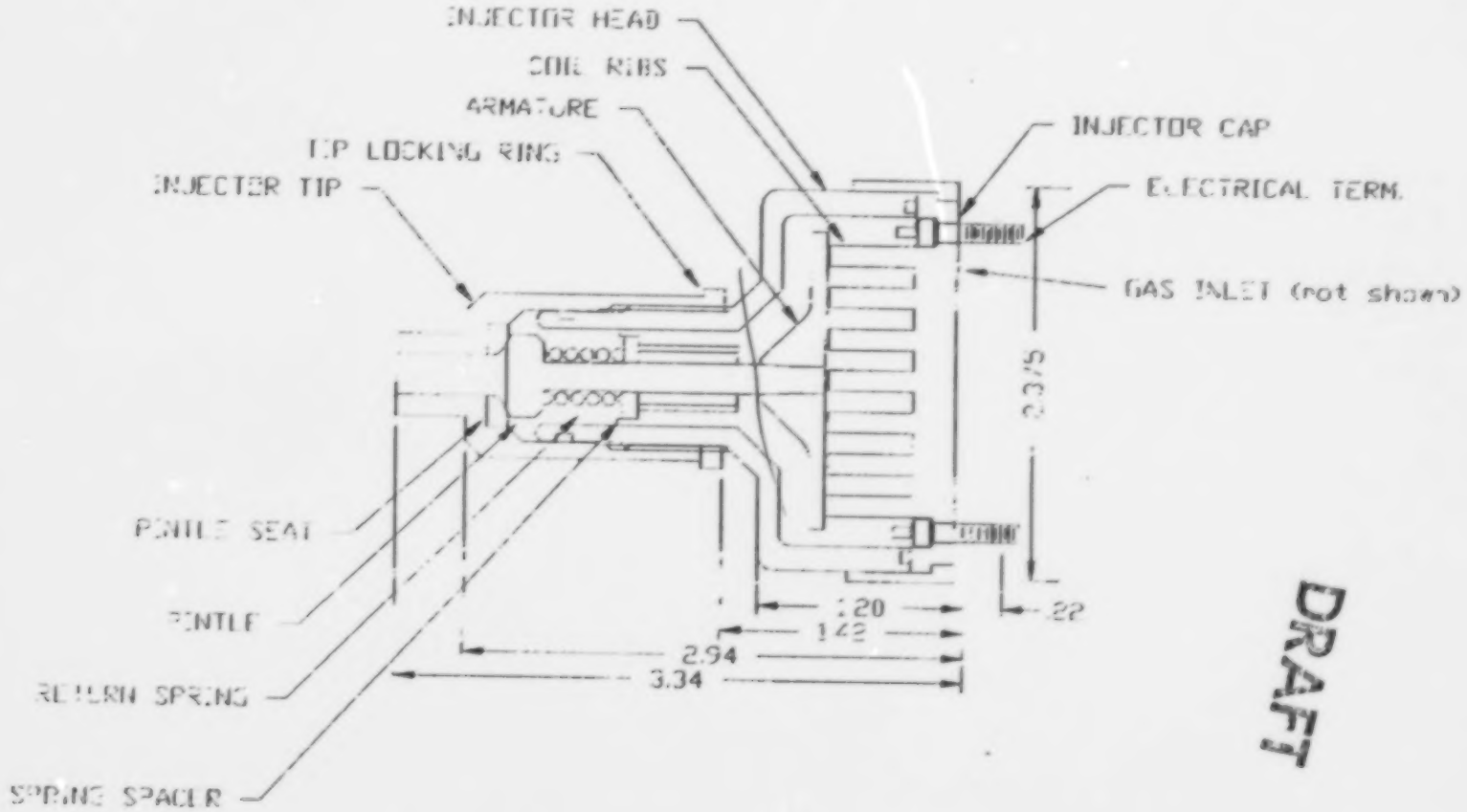
BC RESEARCH

TITLE: MOUNTING BRACKETS & ASS'Y

DWG.NO. 605973-009

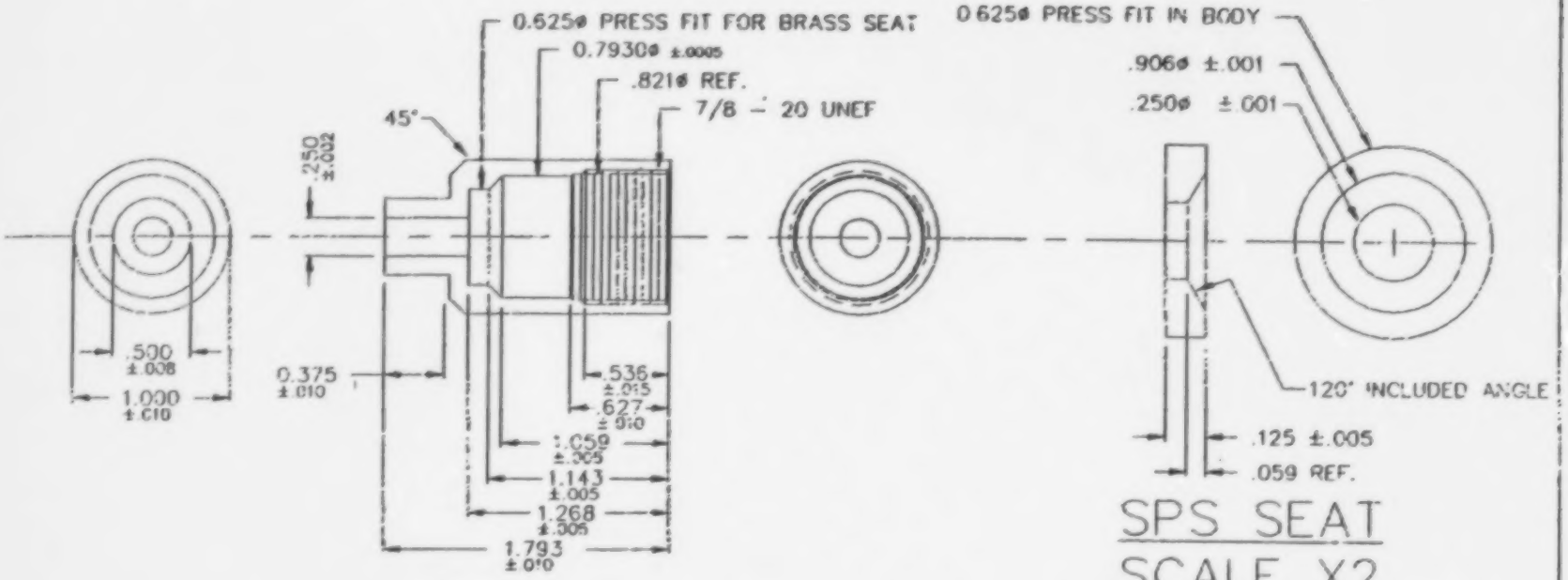
SIZE A

REV.	DESCRIPTION	DATE



DRAFT

TOLERANCES: XX ± .01, XXX ± .005	
TITLE: CGV 100	DATE: SEP 25/89
PART: GAS INJECTOR	
MATERIAL: VARIES	SCALE: 1 to 1
DRAWN BY: CHRIS J. GREEN	SHEET: 1 of 1

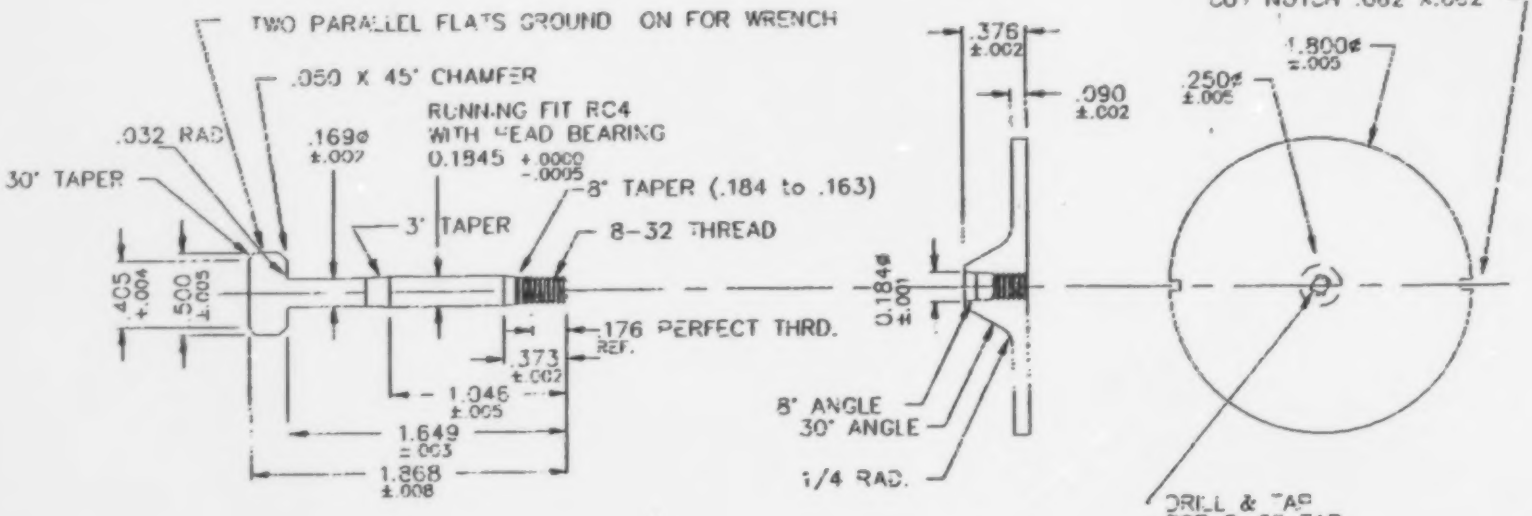


SPS SEAT

SCALE X2

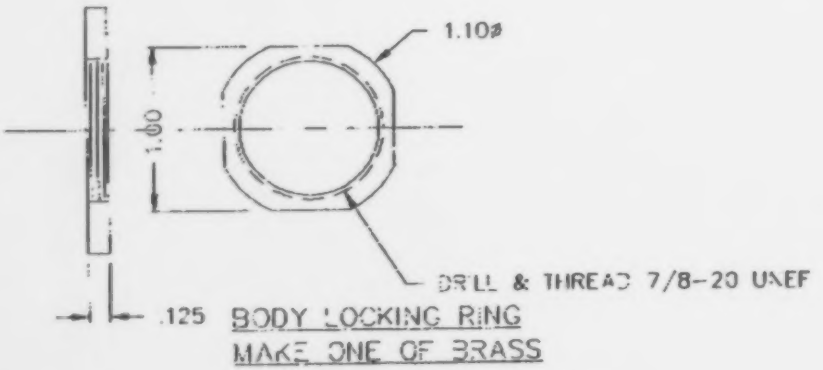
TITLE: CGV 100	TOLERANCES: .xx ±.01 .xxx ±.005 / DATE: NOV. 6/89
PART: INJECTOR BODY	
MATERIAL: SPS/ STAINLESS 303	SCALE: 1 to 1
DRAWN BY: CHRIS J. GREEN	SHEET: 2 of 8

03/15/1990 14:59 ORTECHINTERNATIONAL 6610311 416 823 1446 P.05

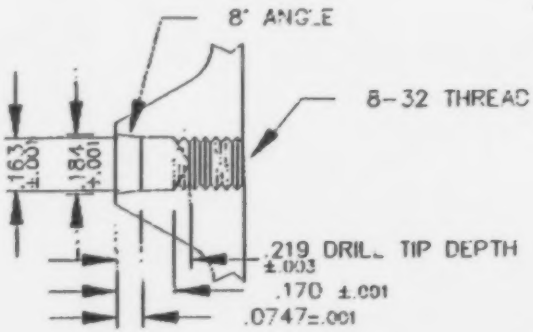


PINTLE ARMATURE CONNECTING ROD
MAKE ONE OF SPS

INJECTOR ARMATURE
MAKE ONE OF MILD STEEL

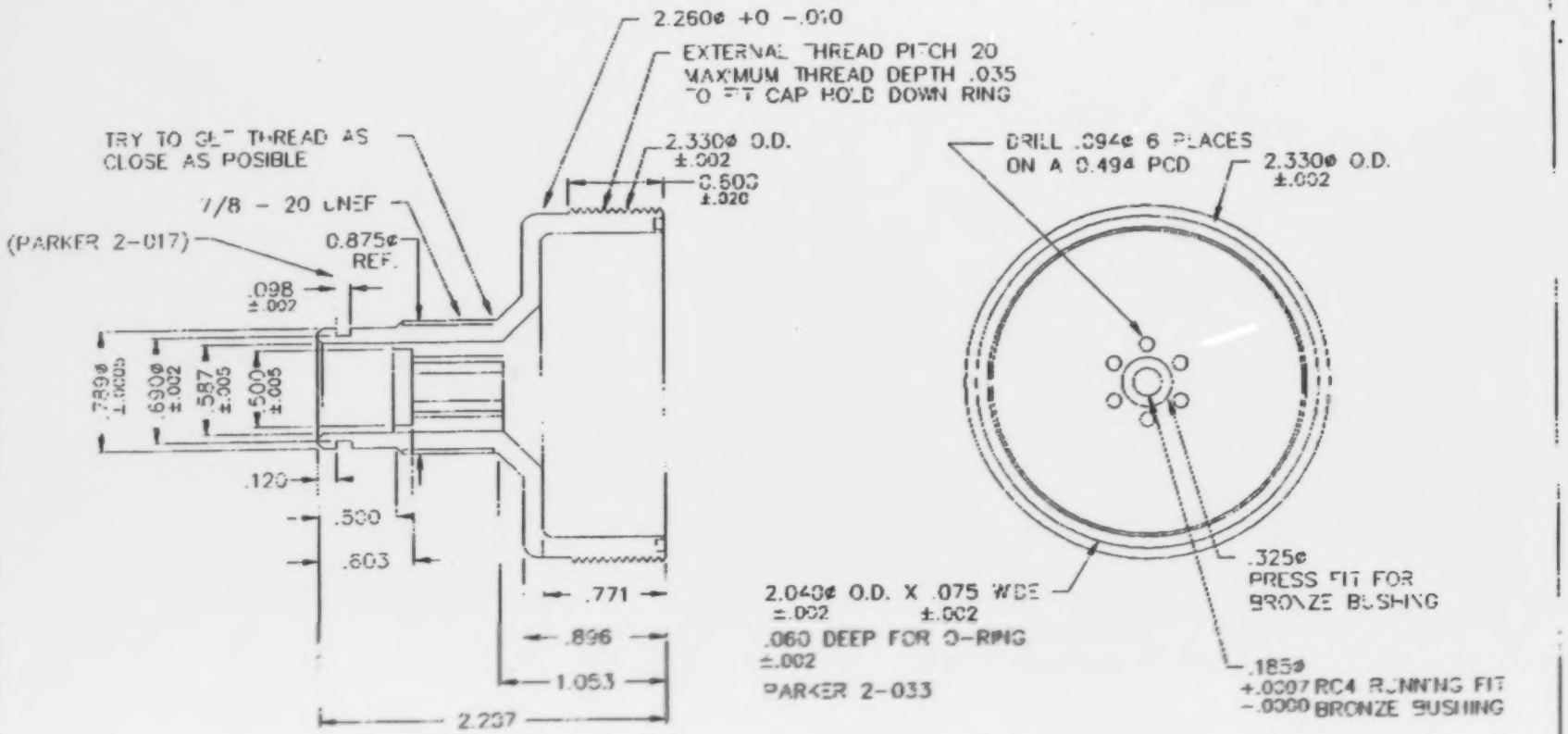


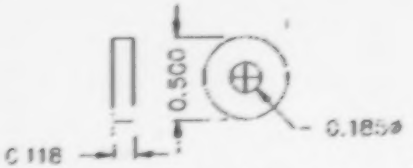
BODY LOCKING RING
MAKE ONE OF BRASS



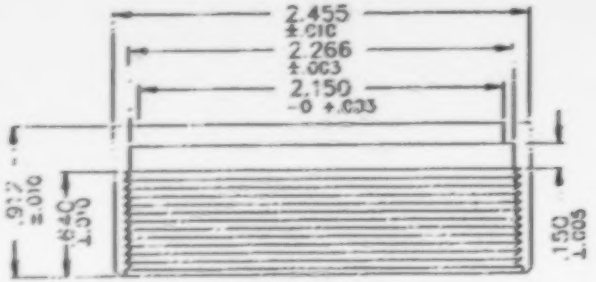
TITLE: CGV 100	DATE: NOV. 6/89
PART: PINTLE/ARMATURE	
MATERIAL: SPS / MILD STEEL	SCALE: 1 to 1
DRAWN BY: CHRIS J. GREEN	SHEET: 3 of 6

TOLERANCES: .XX ±.01 .XXX ±.005



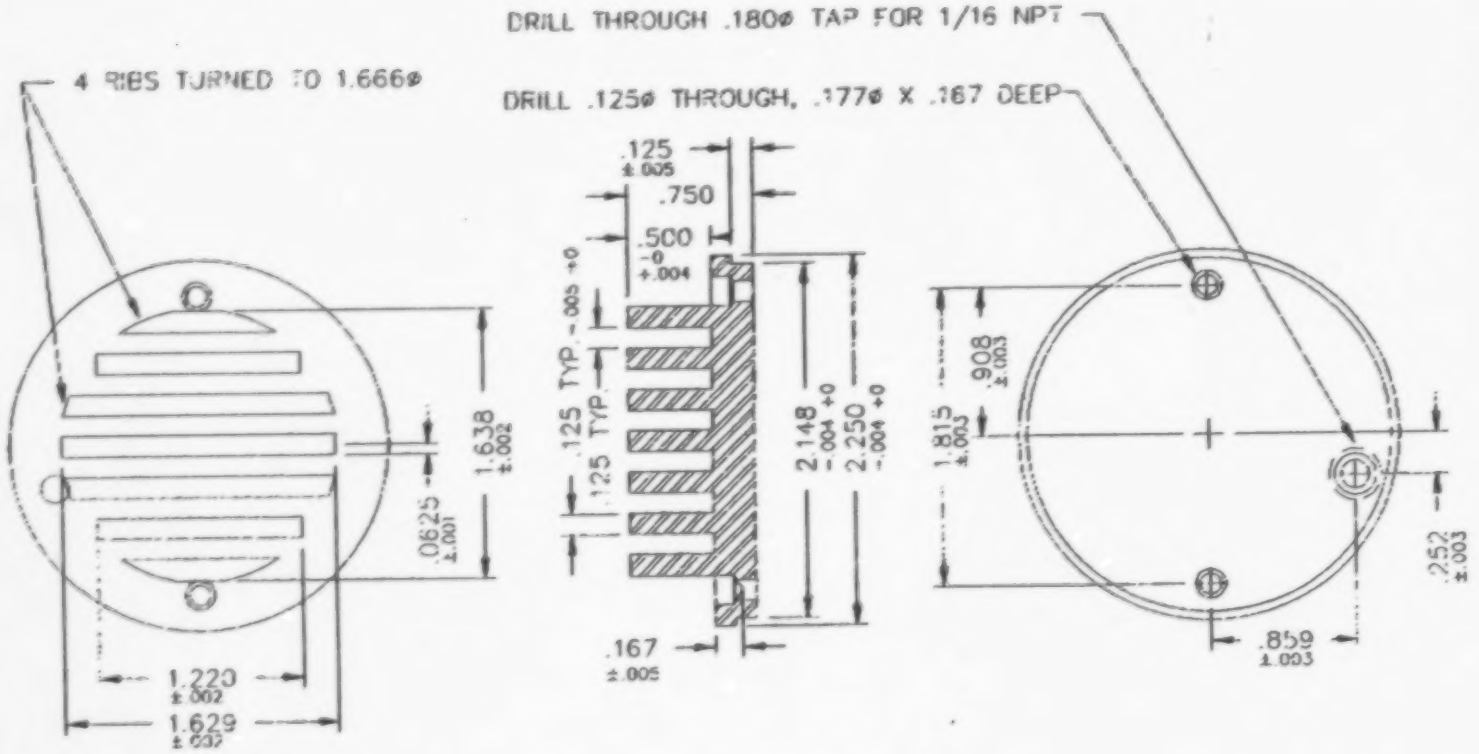


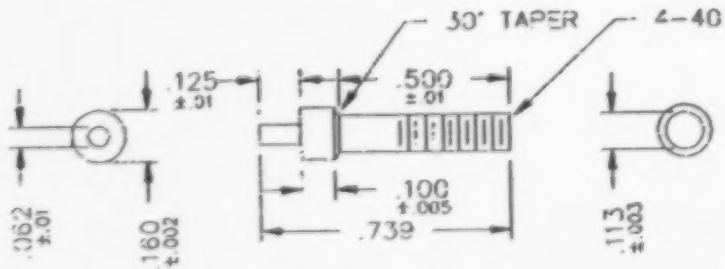
SPRING SPACER
MAKE ONE OF STAINLESS
NOTE: OD MUST SLIDE FIT
IN HEAD .5ø BORE



CAP LOCKING RING
MAKE ONE OF BRASS
TO FIT HEAD

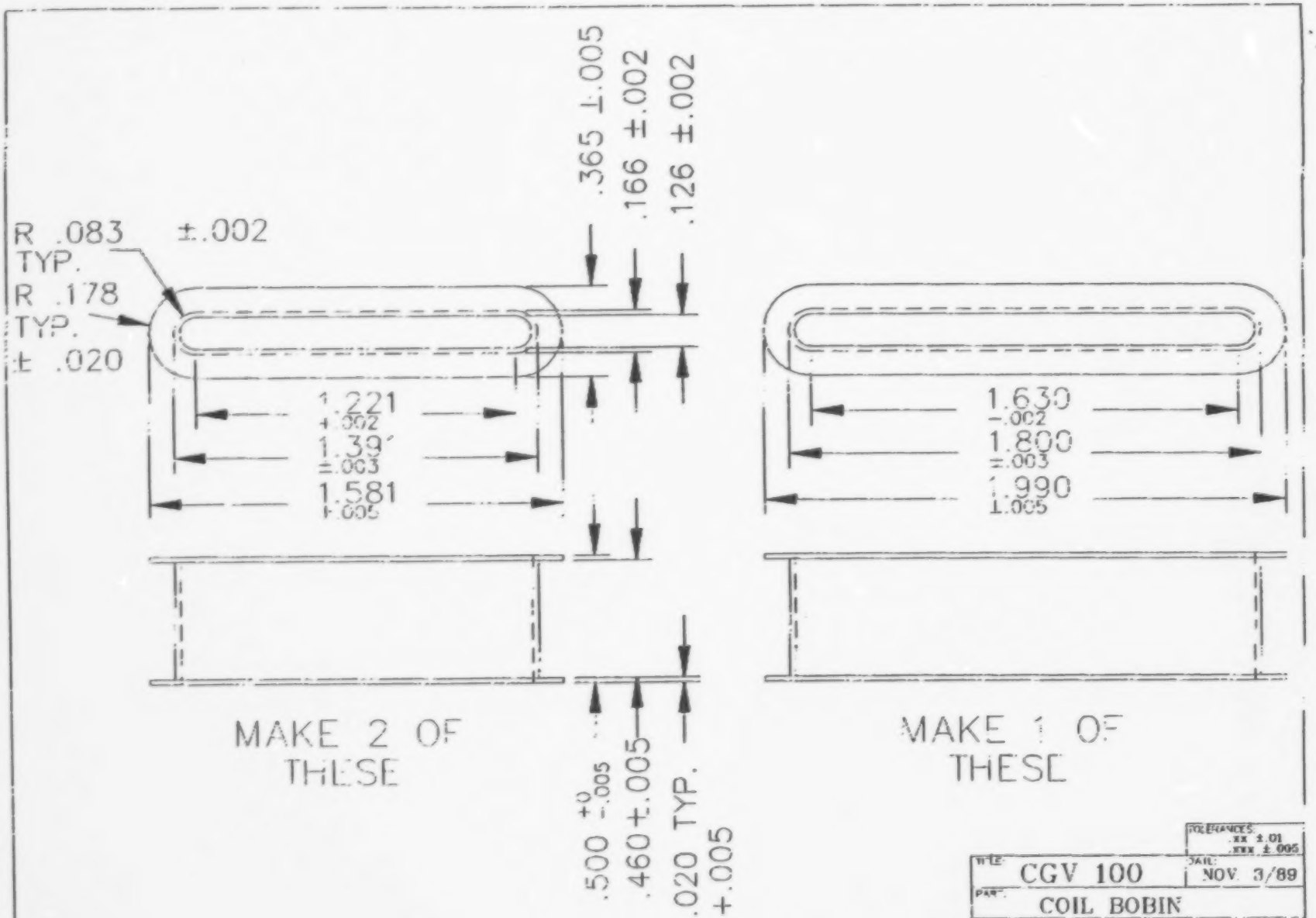
RE: CGV 100	DATE: NOV. 6/89
PART: INJECTOR HEAD	
MATERIAL: BRASS	SCALE: 1 to 1
DRAWN BY: CHRIS J. GREEN	SHEET: 4 of 6





SCALE X2

TOLERANCES: .xx ±.01 .xxx ±.005	
TITLE: CGV 100	DATE: SEP 28/89
PART: INJECTER CAP	
MATERIAL: MILD STEEL	SCALE: 1 to 1
DRAWN BY: CHRIS J. GREEN	SHEET: 5 of 8



TOLERANCES: .xx ±.01 .xxx ±.005	
TITLE: CGV 100	DATE: NOV. 3/89
PART: COIL BOBIN	
MATERIAL: DELRIN	SCALE: 2 to 1
DRAWN BY: CHRIS J. GREEN	SHEET: 6 of 6